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(54) **SWITCH FOR USE IN MICROELECTROMECHANICAL SYSTEMS (MEMS) AND MEMS DEVICES INCORPORATING SAME**

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(51) **Int. Cl.**
H01H 51/22 (2006.01)
H01H 57/00 (2006.01)

(52) **U.S. Cl.** **335/78**; 200/181; 335/83

(58) **Field of Classification Search** 335/78, 335/83; 200/181

See application file for complete search history.

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Assistant Examiner — Alexander Talpalatskiy
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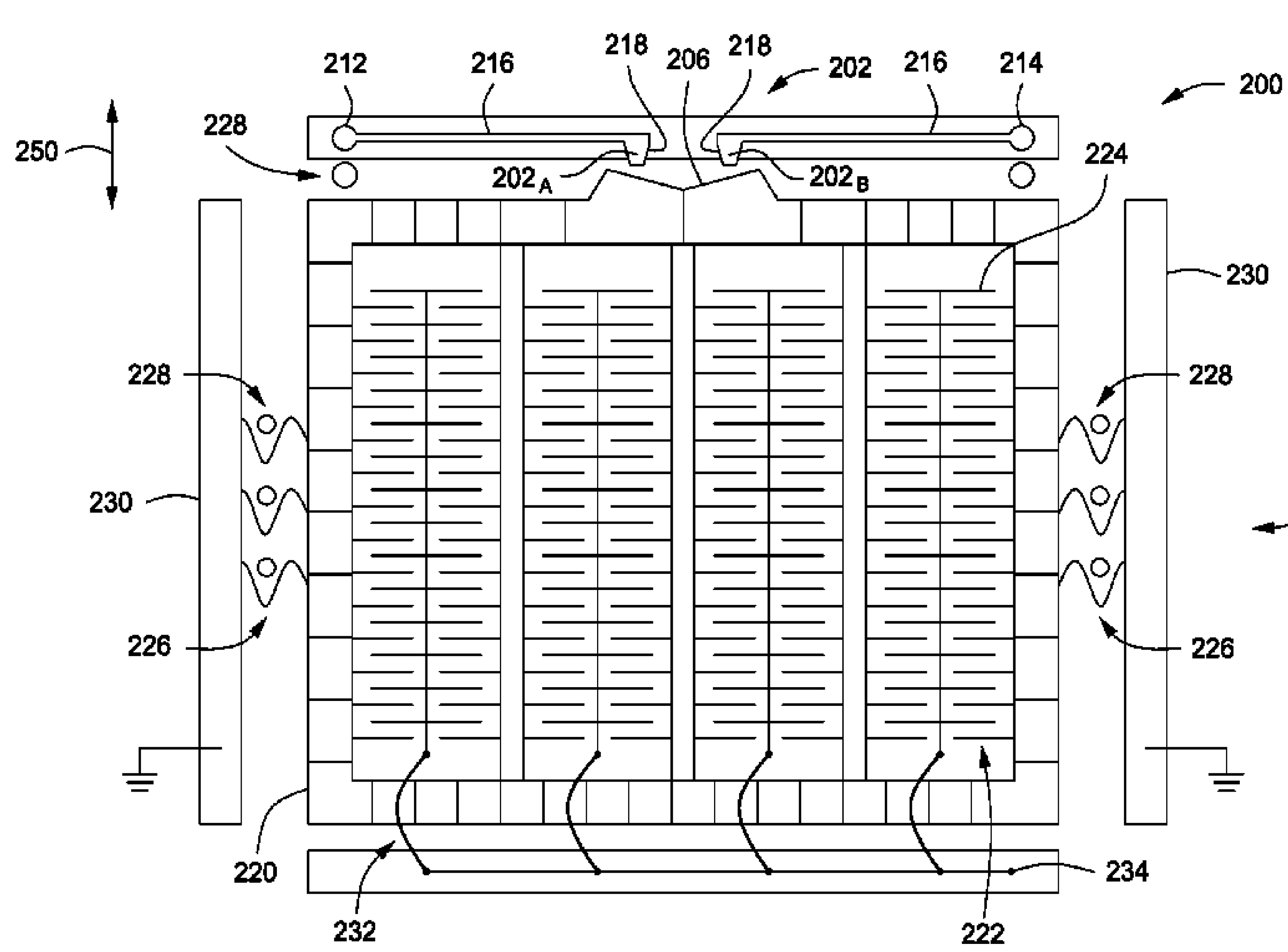
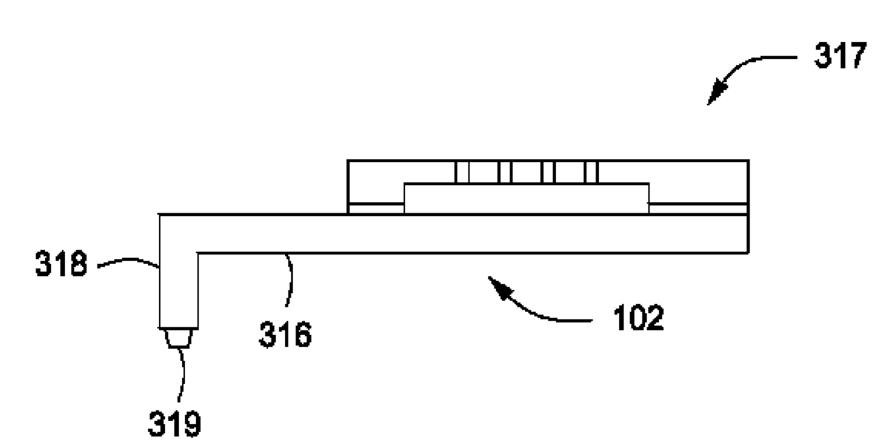
(57) **ABSTRACT**

Embodiments of the present invention provide microelectromechanical systems (MEMS) switching methods and apparatus having improved performance and lifetime as compared to conventional MEMS switches. In some embodiments, a MEMS switch may include a resilient contact element comprising a beam and a tip configured to wipe a contact surface; and a MEMS actuator having an open position that maintains the tip and the contact surface in a spaced apart relation and a closed position that brings the tip into contact with the contact surface, wherein the resilient contact element and the MEMS actuator are disposed on a substrate and are movable in a plane substantially parallel to the substrate. In some embodiments, various contact elements are provided for the MEMS switch. In some embodiments, various actuators are provided for control of the operation of the MEMS switch.

24 Claims, 15 Drawing Sheets





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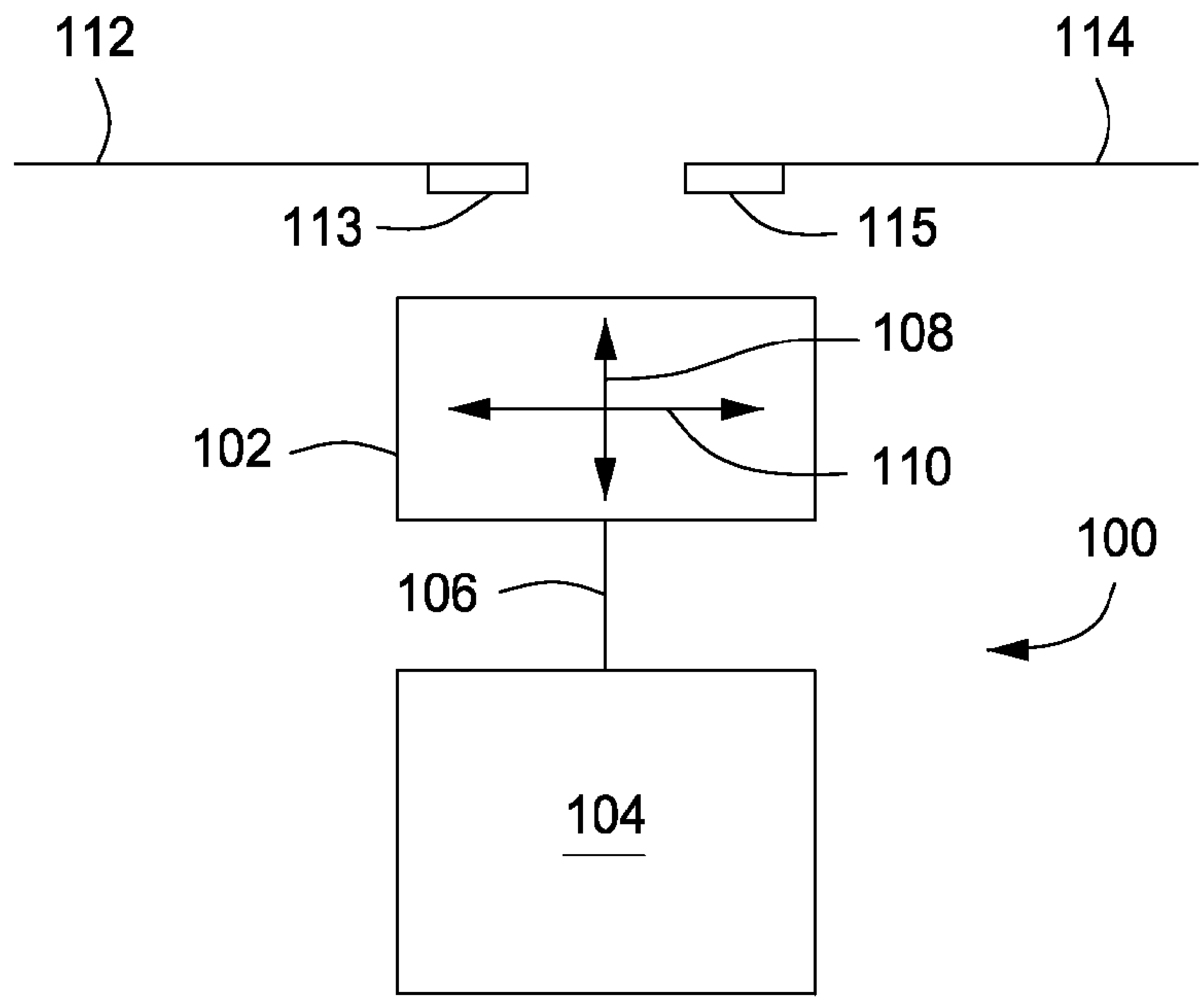
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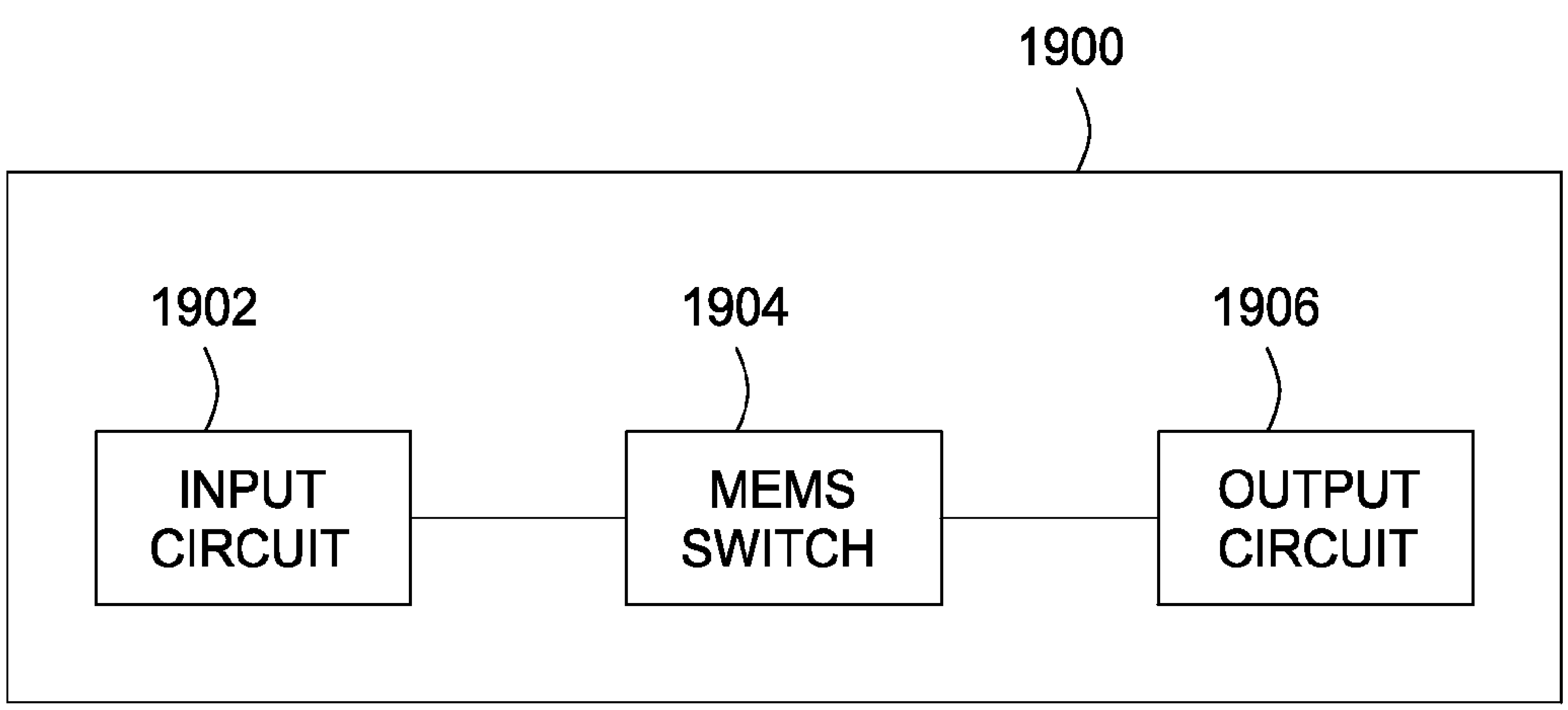
FIG. 1


1900
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INPUT CIRCUIT
MEMS SWITCH
OUTPUT CIRCUIT

FIG. 19

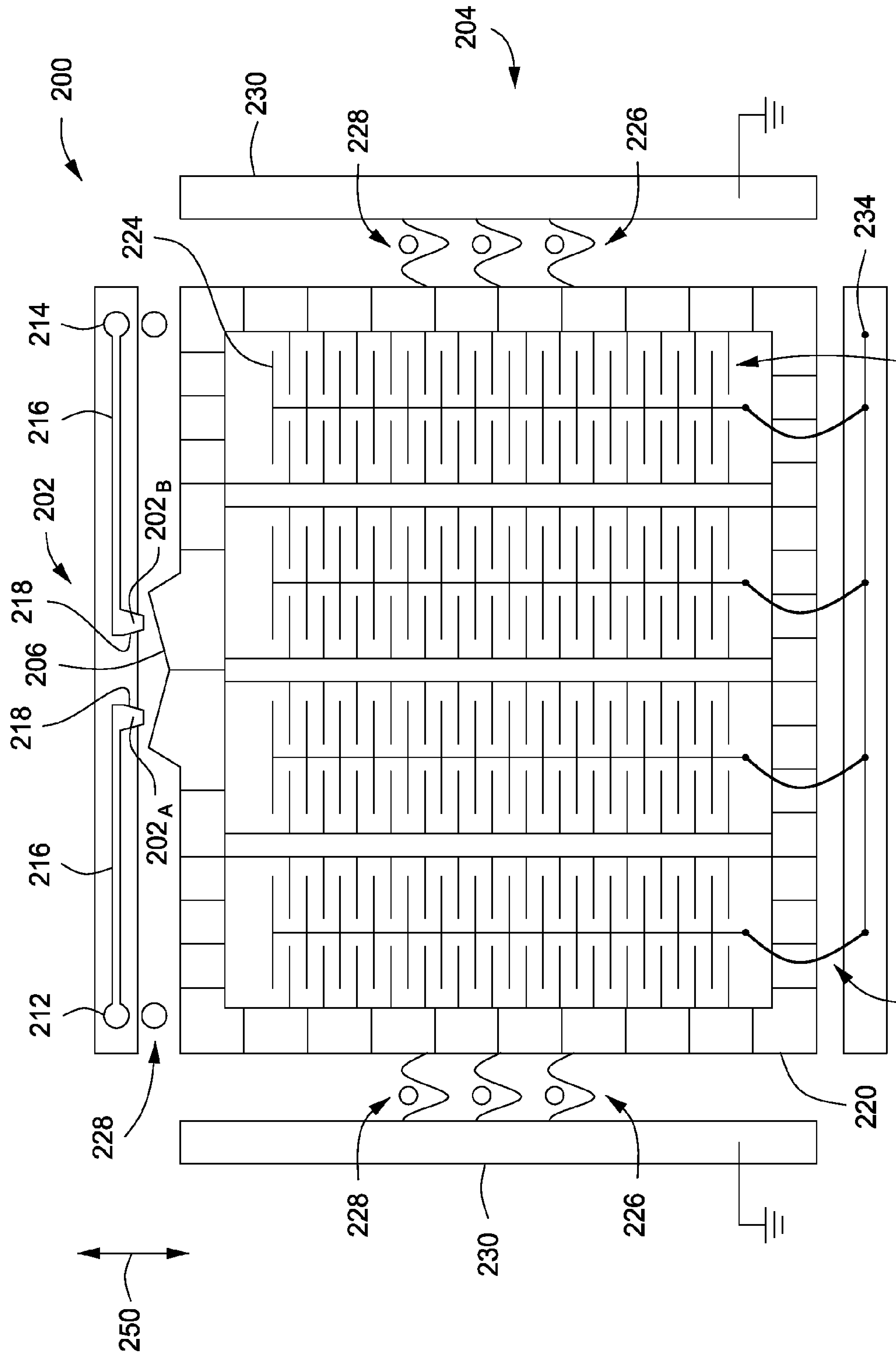
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FIG. 2

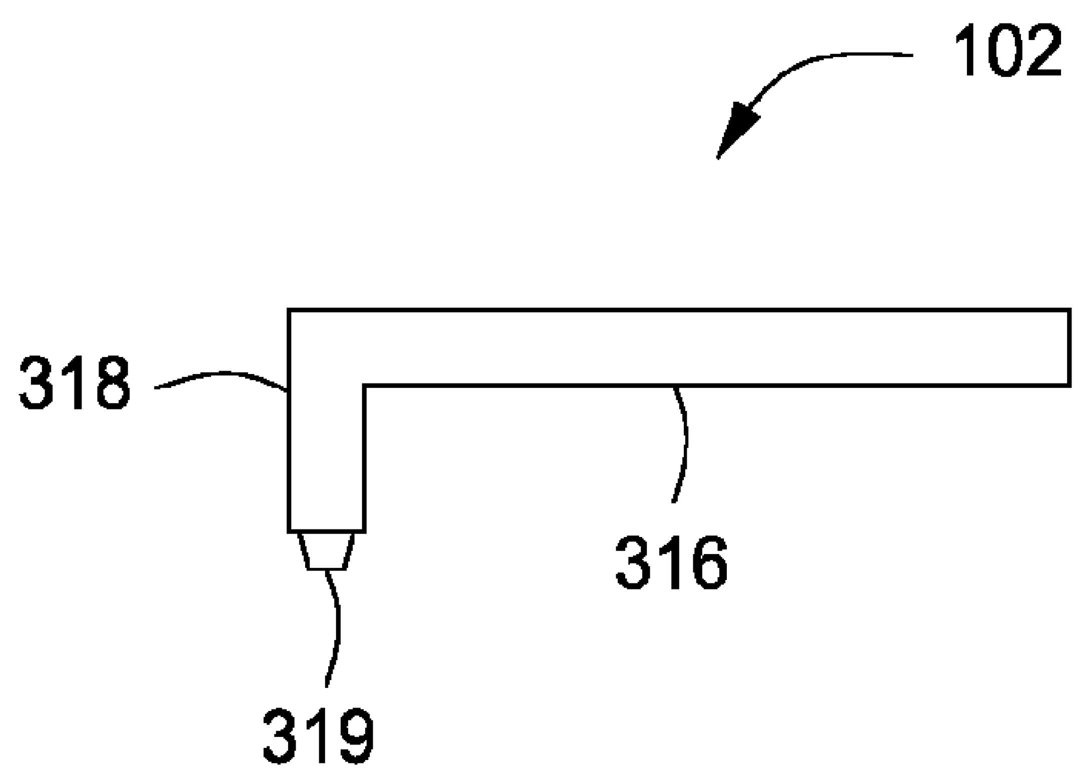

FIG. 3A

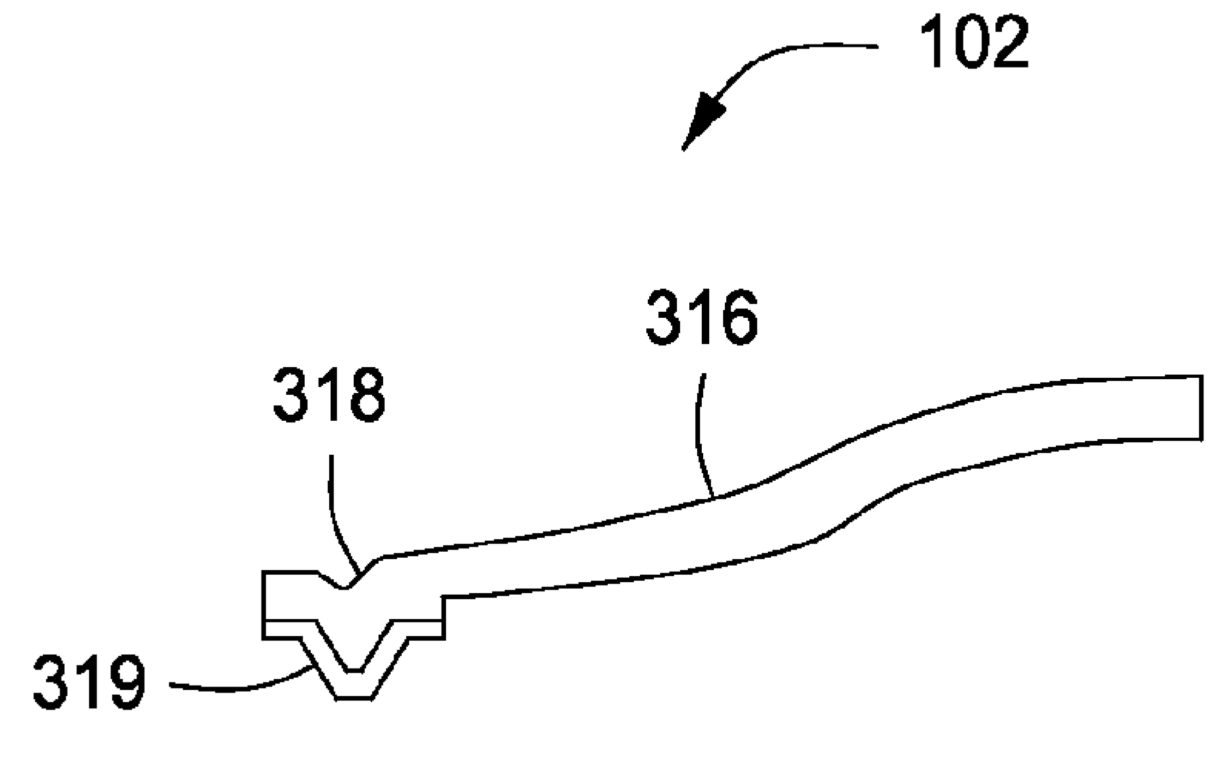

FIG. 3B

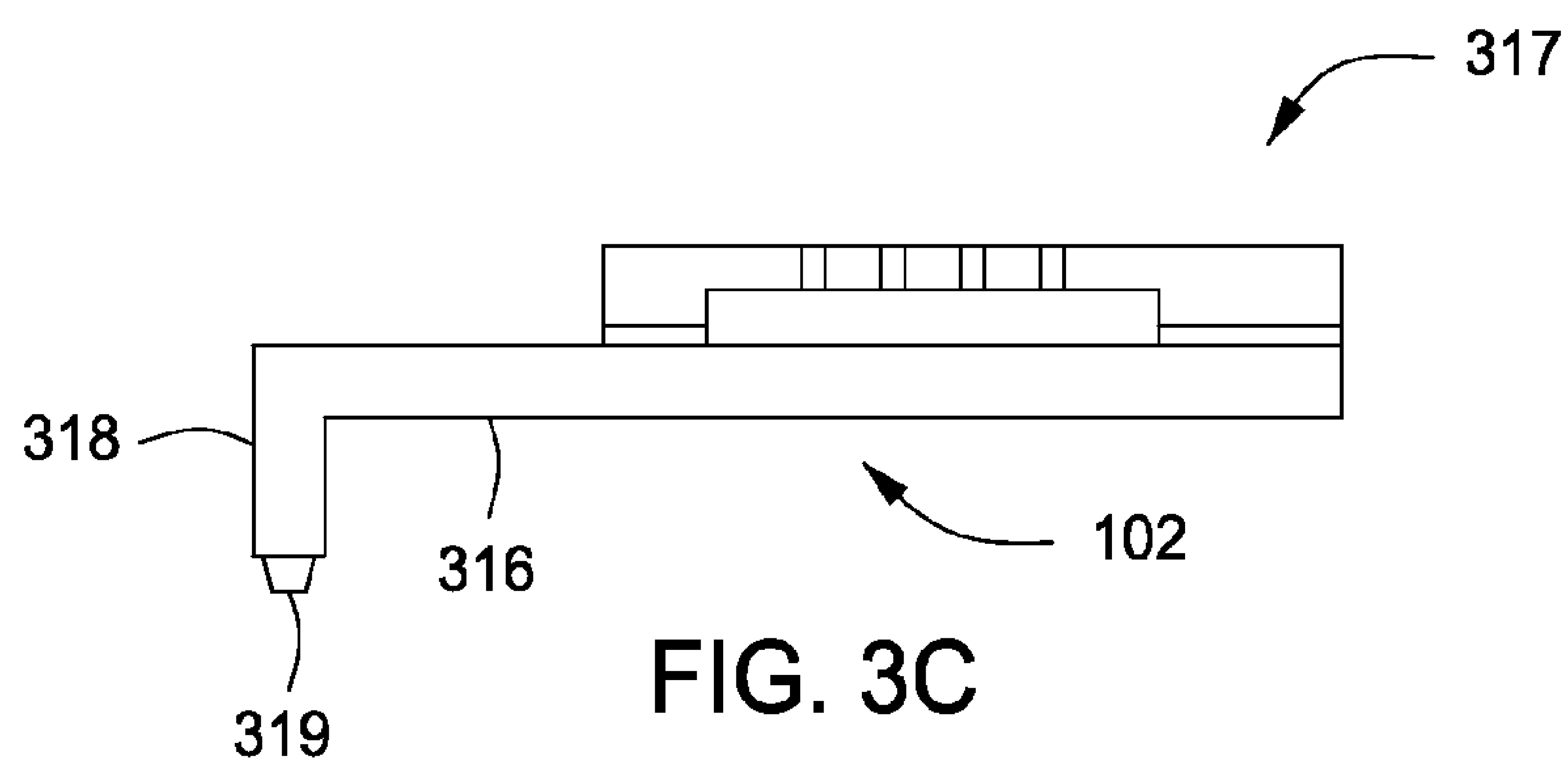

FIG. 3C

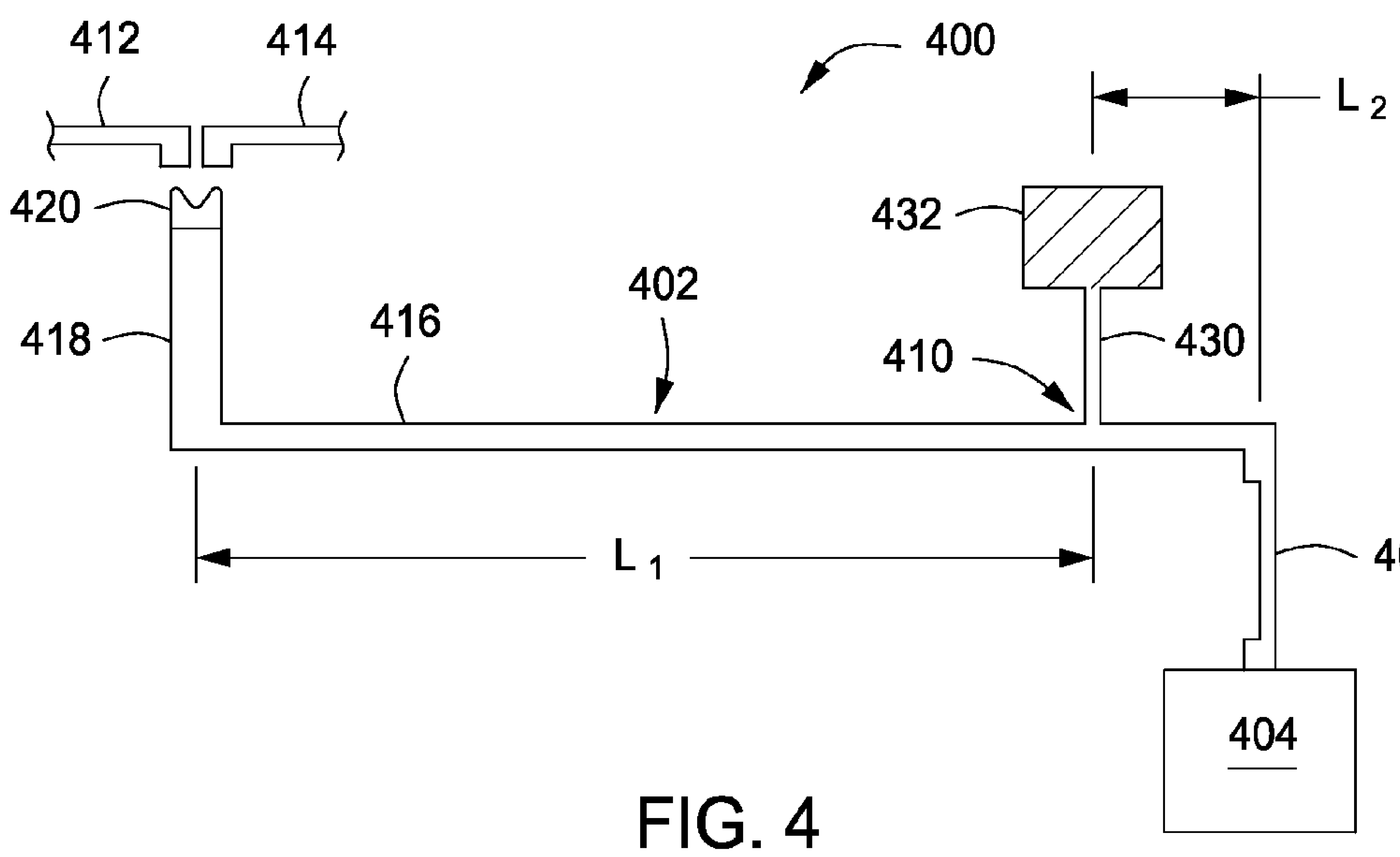

FIG. 4

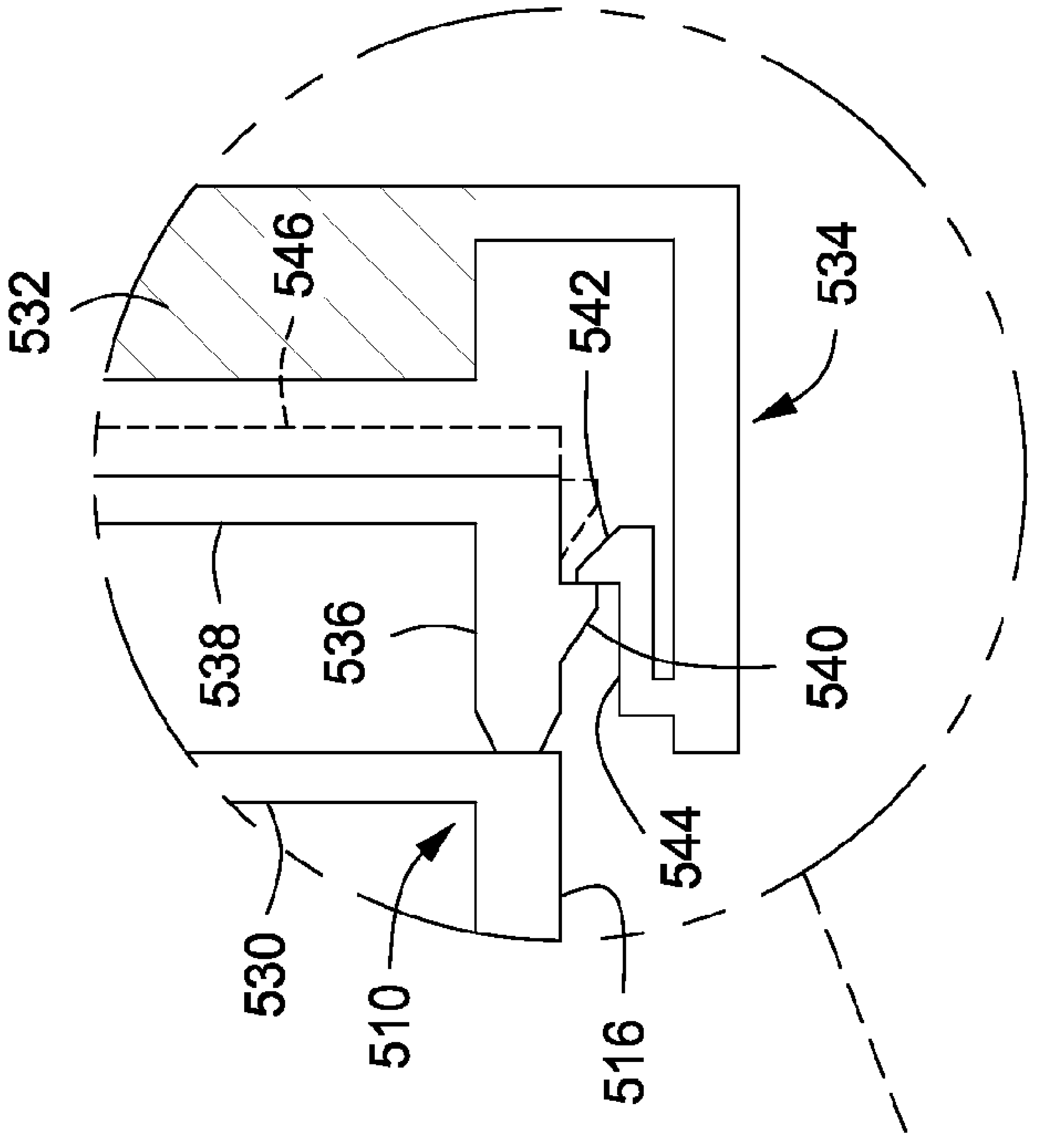
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FIG. 5A

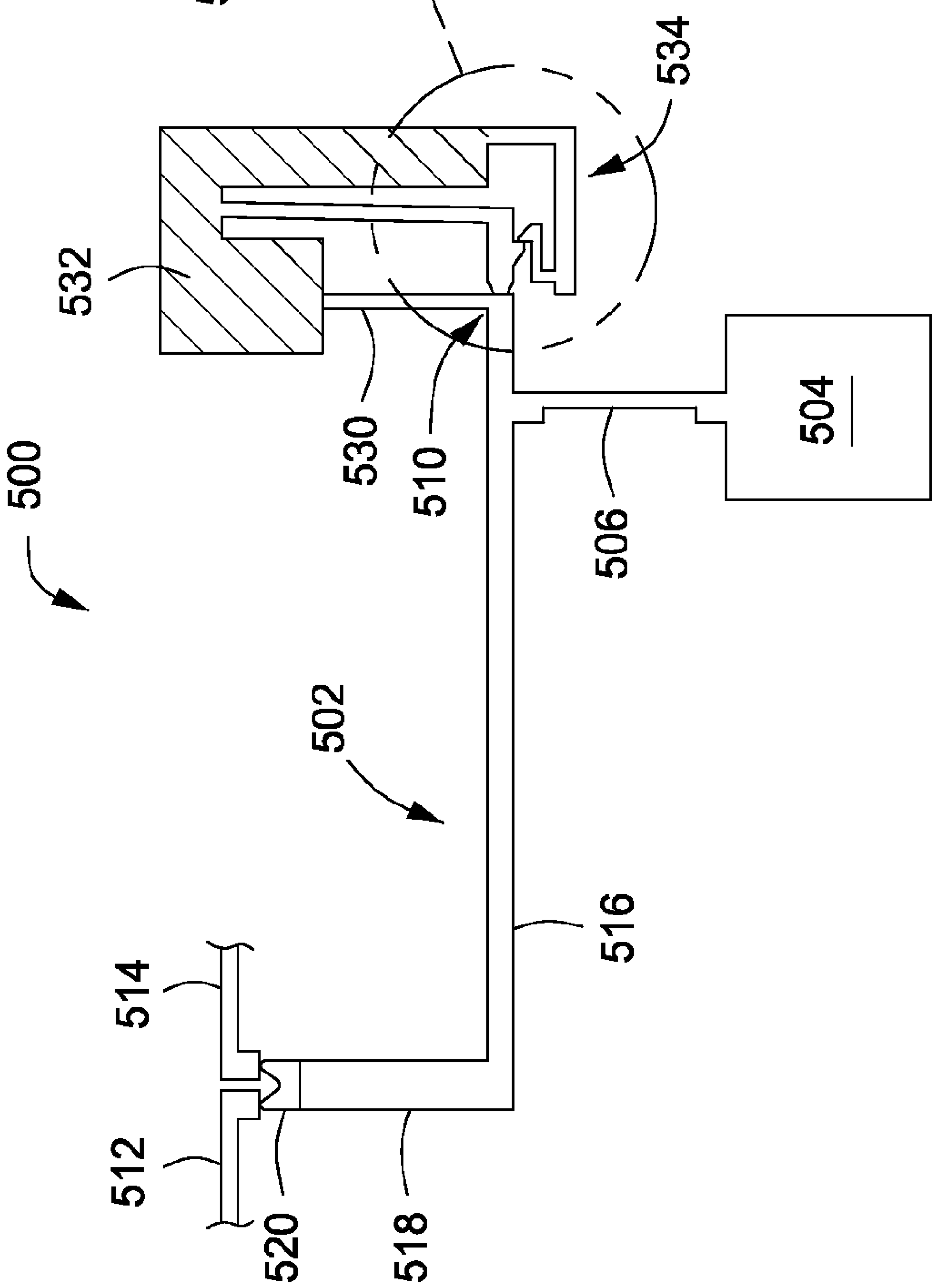
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FIG. 5

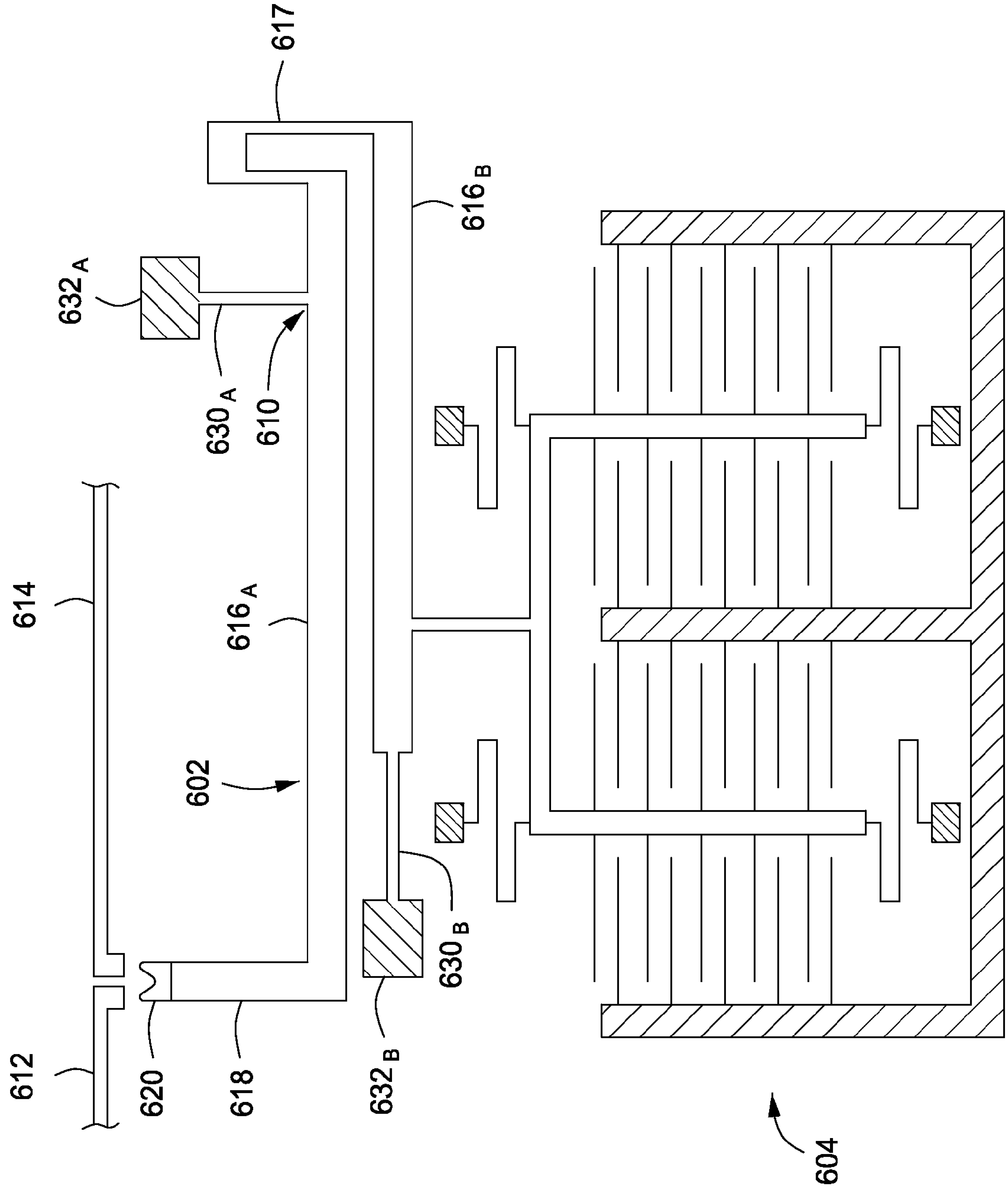
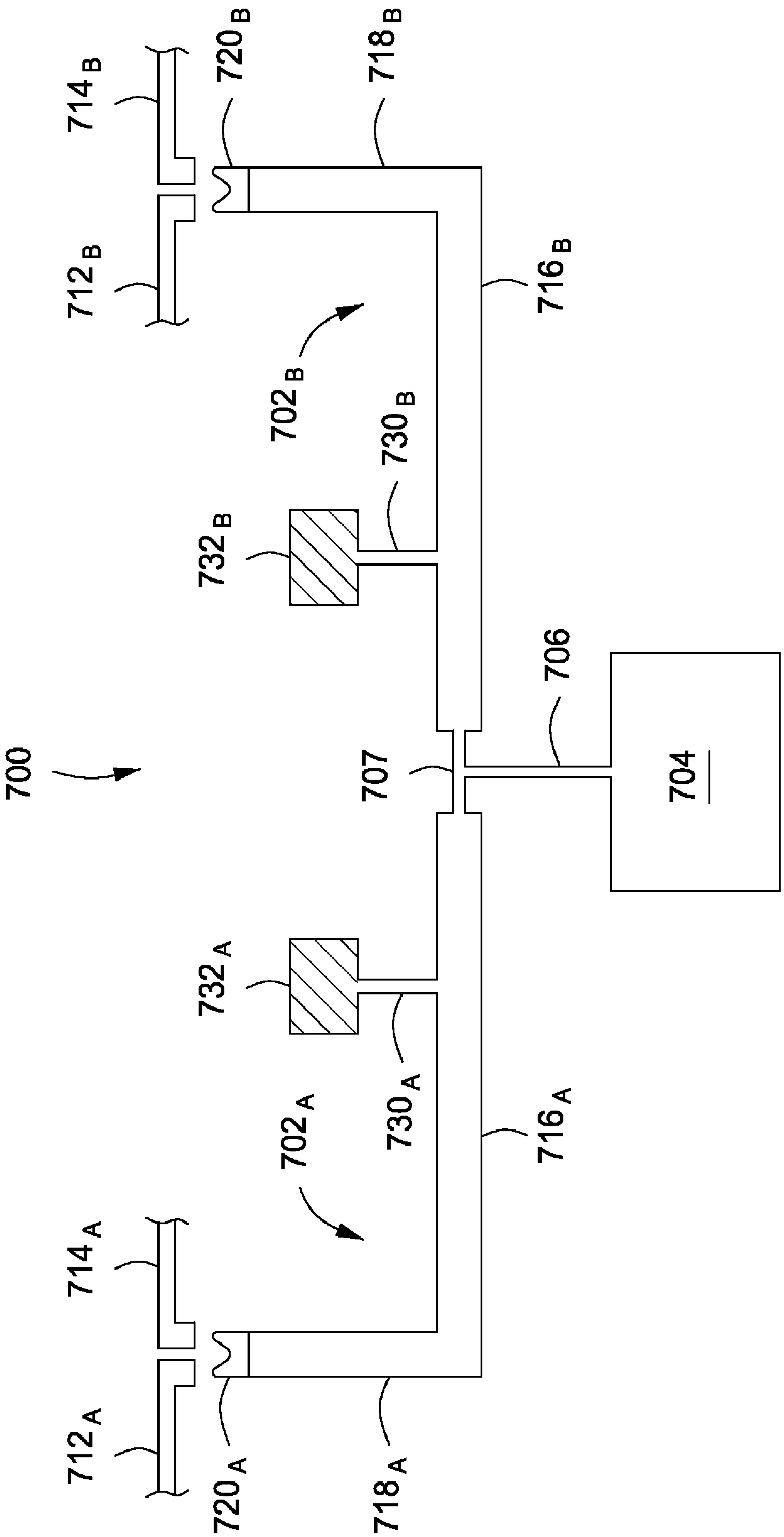


FIG. 6



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730_{B}
732_{B}
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730_{A}
702_{A}
716_{A}
714_{A}
712_{A}
720_{A}
718_{A}

FIG. 7

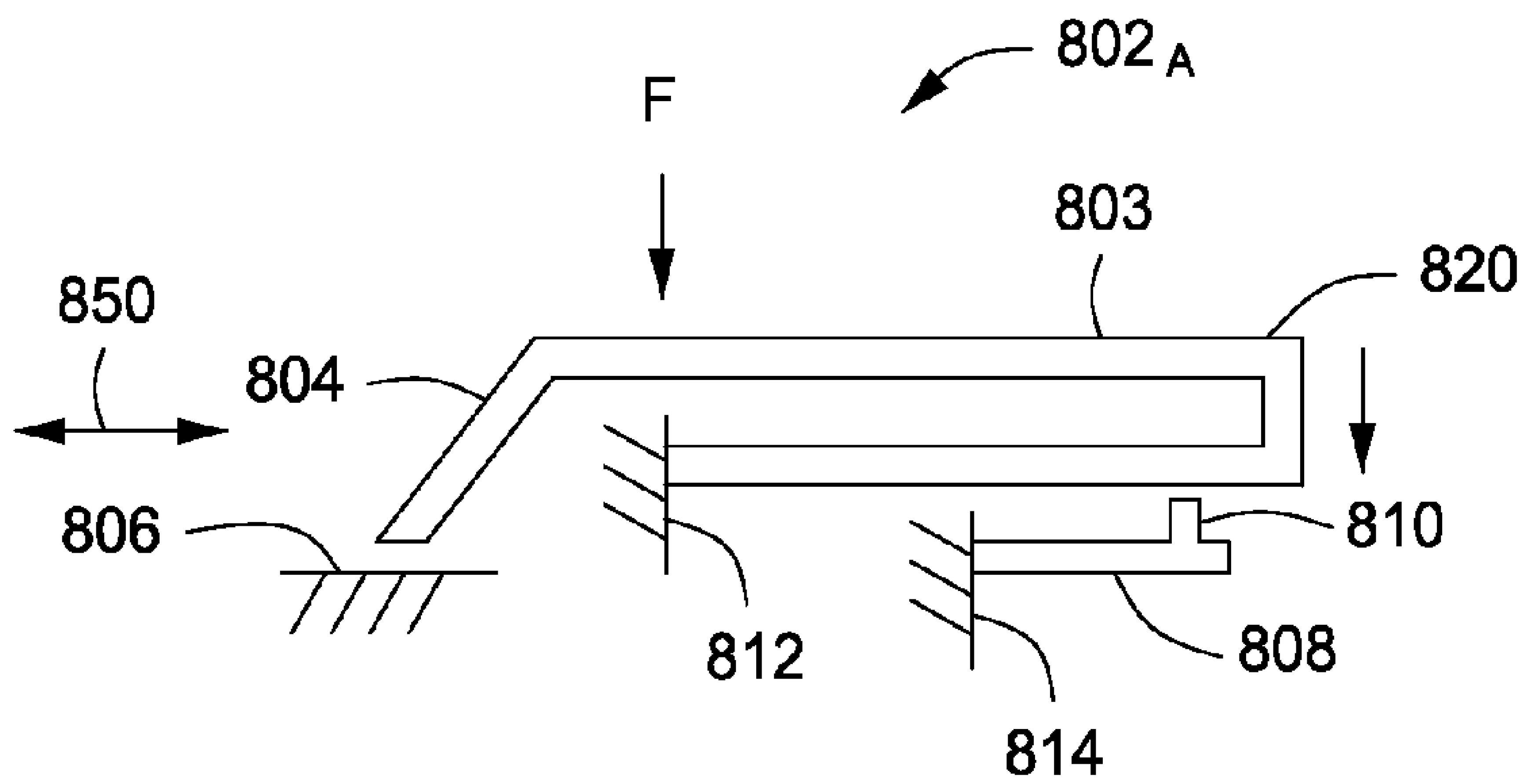


FIG. 8A

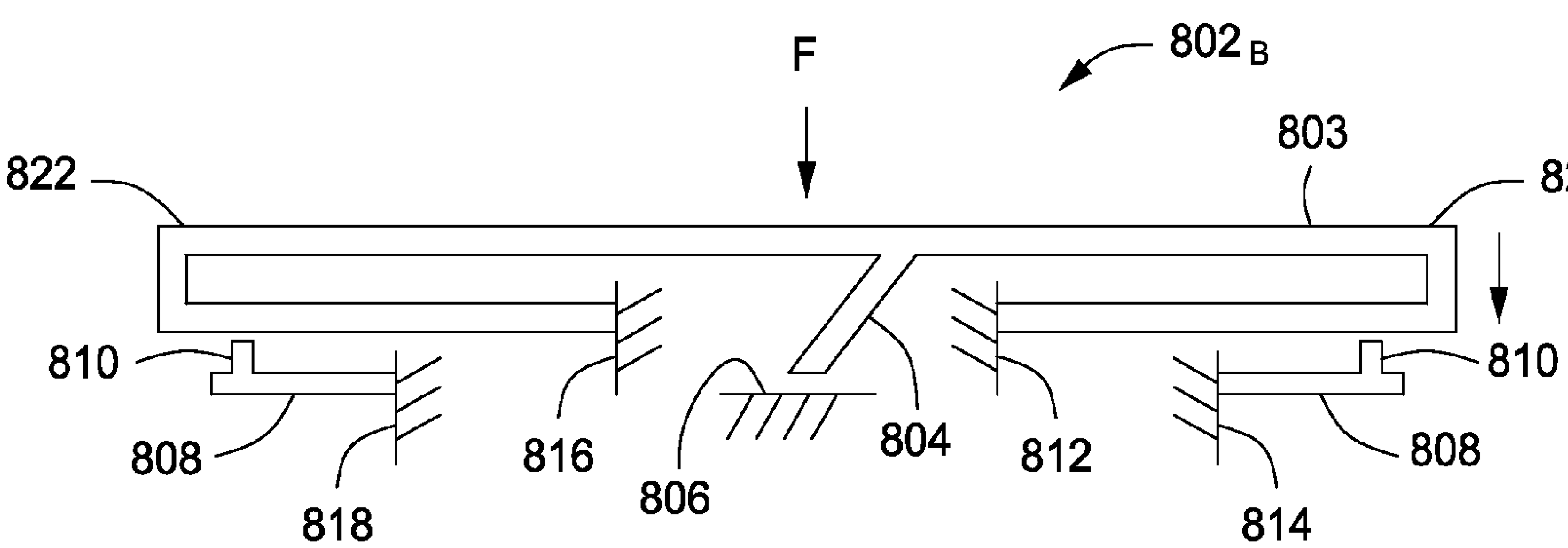


FIG. 8B

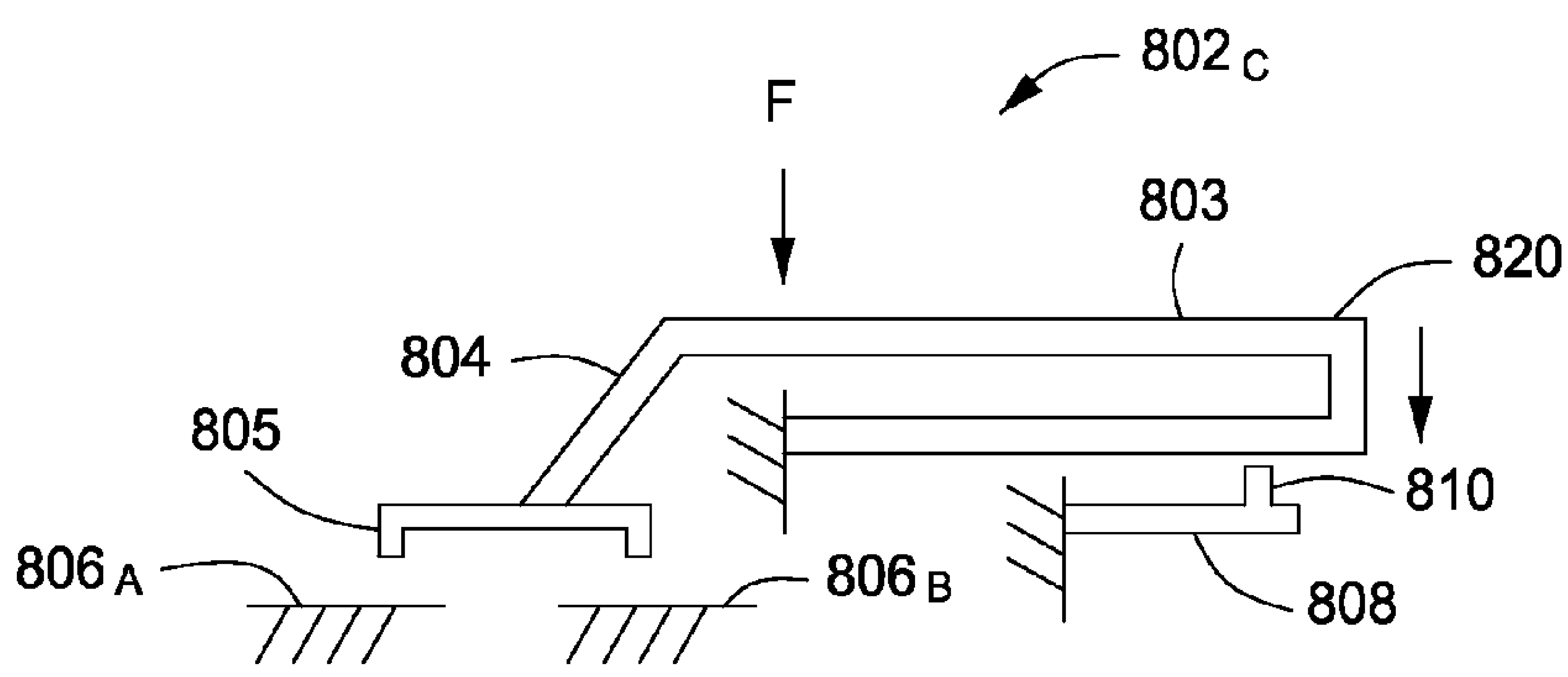


FIG. 8C

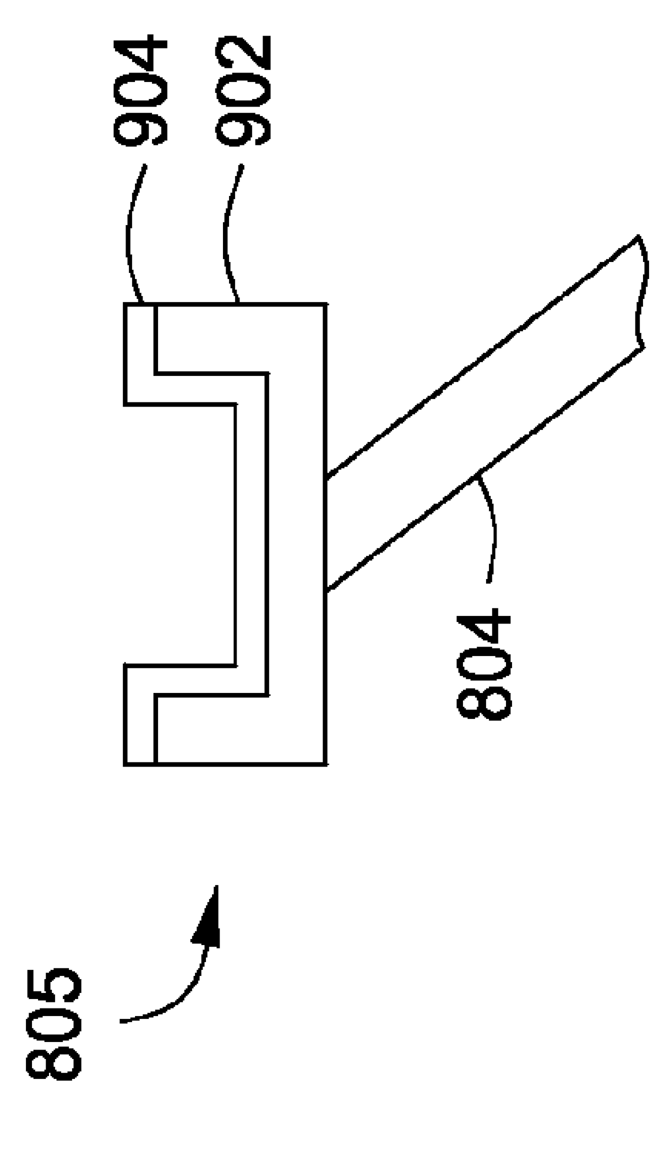


FIG. 9A

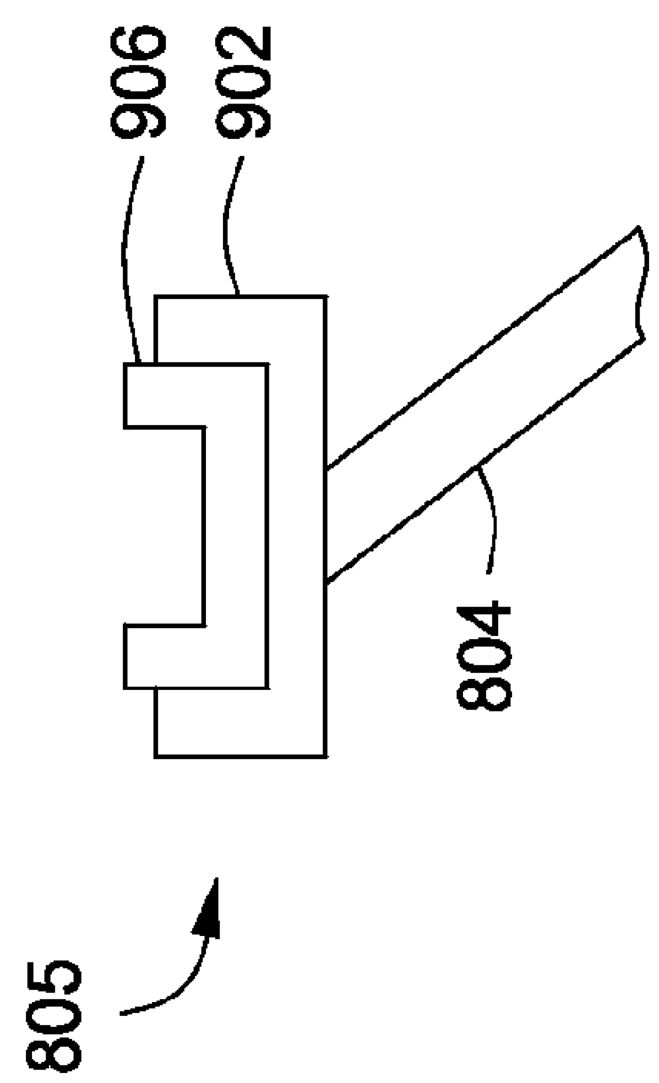


FIG. 9B

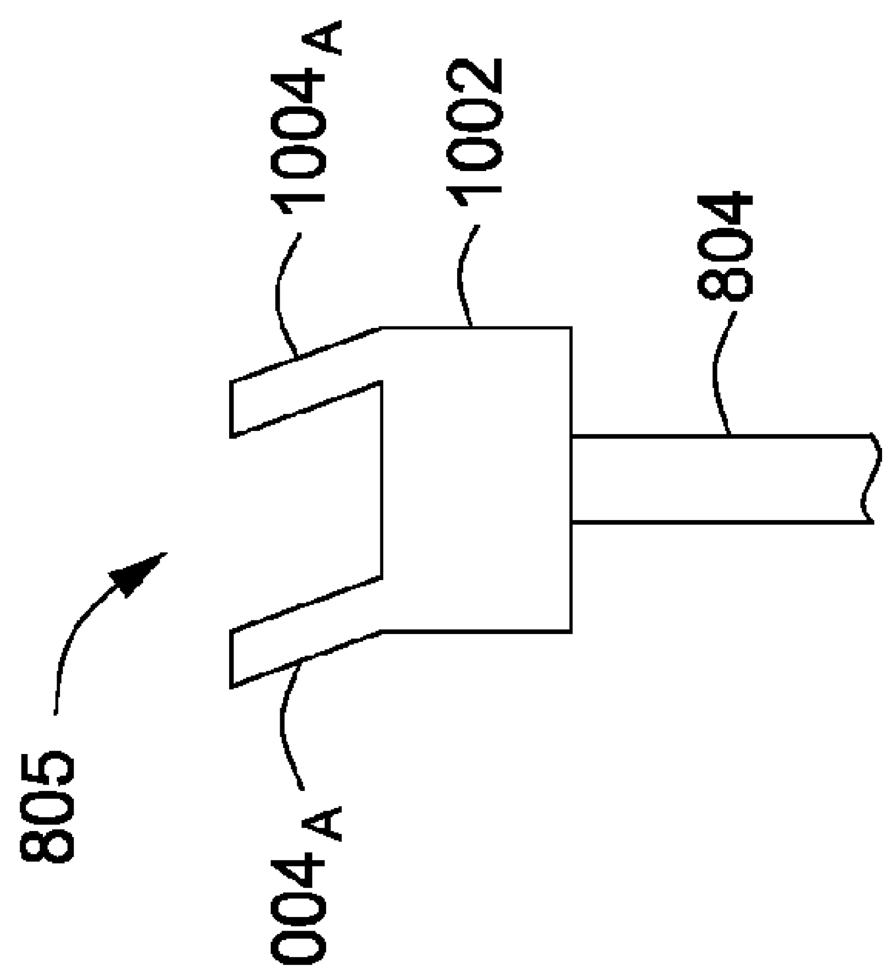


FIG. 10A

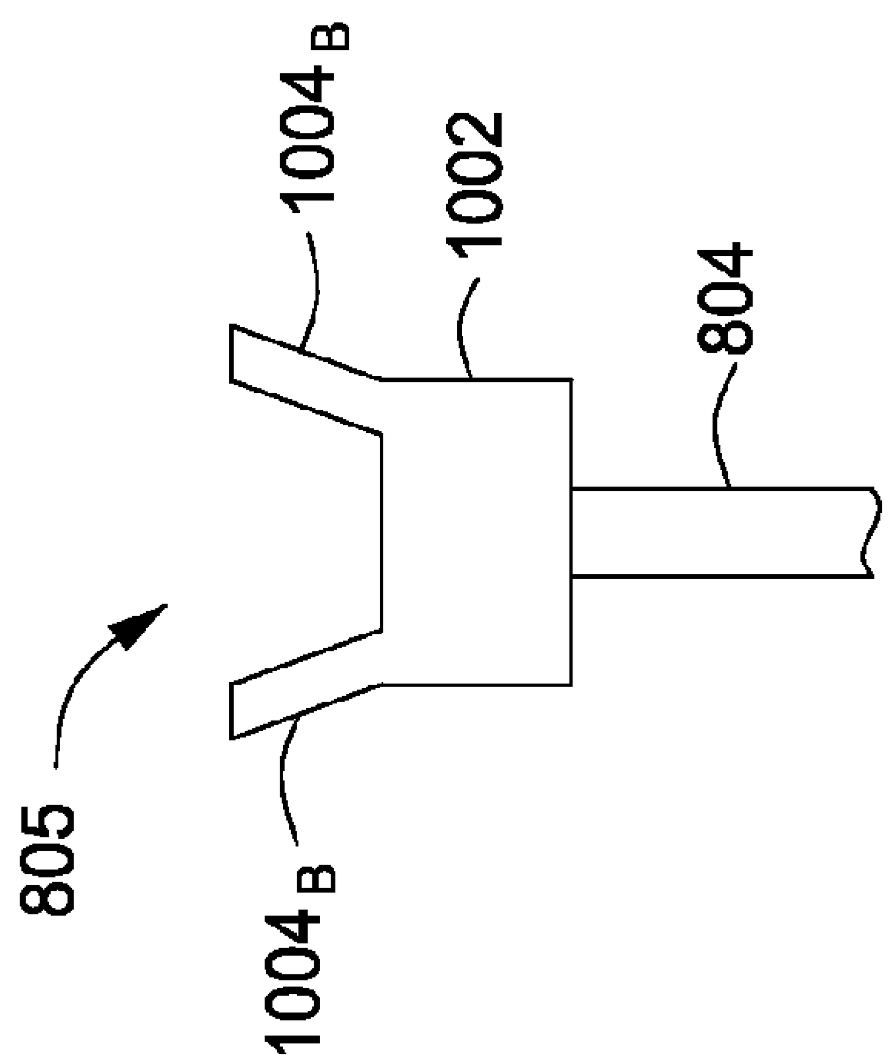


FIG. 10B

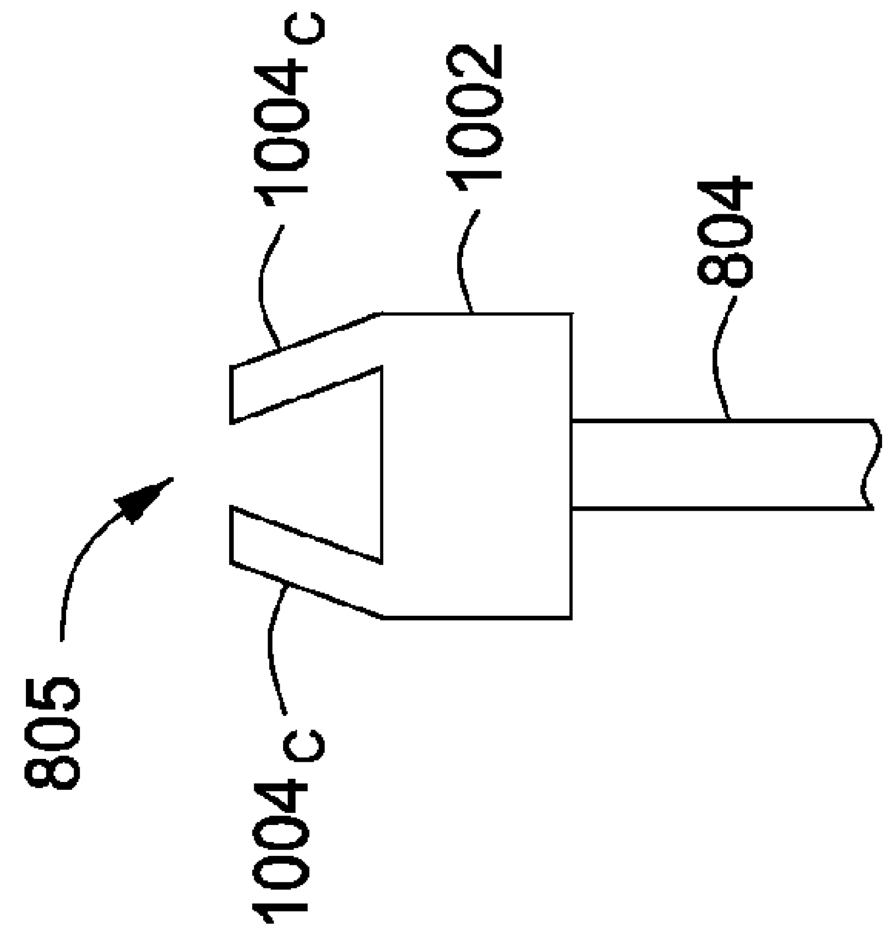


FIG. 10C

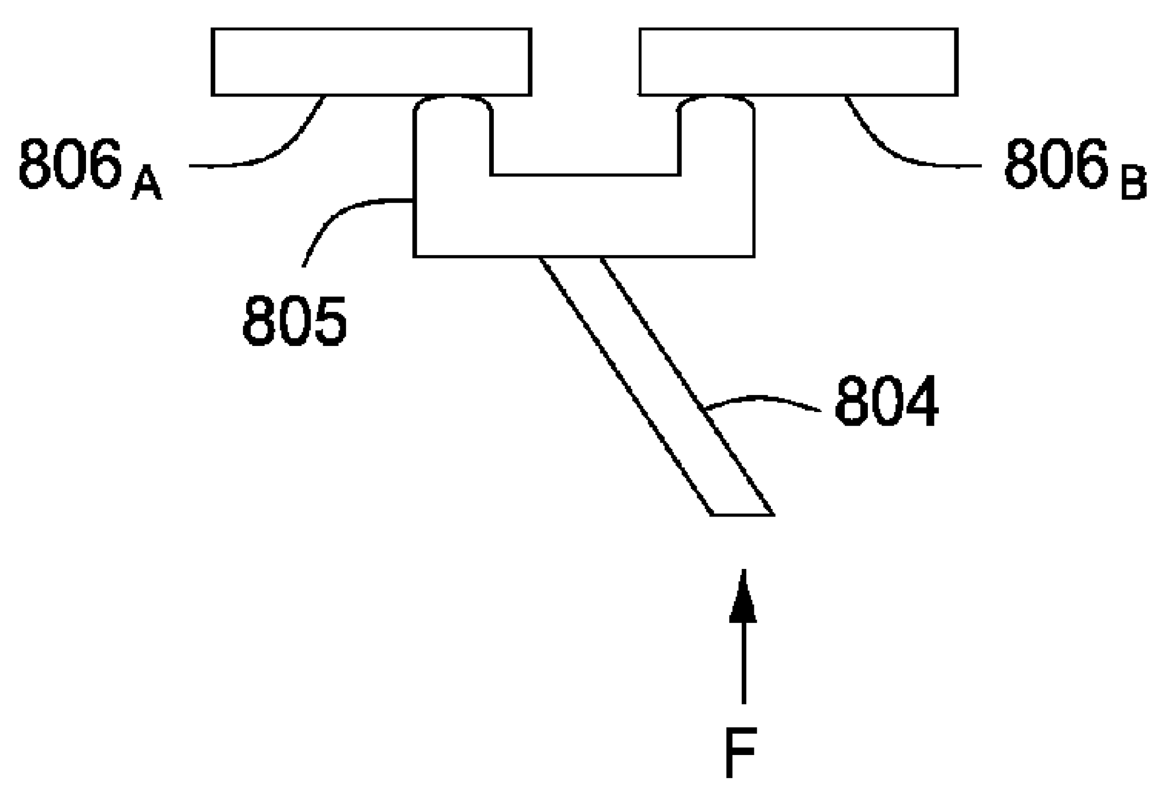


FIG. 11A

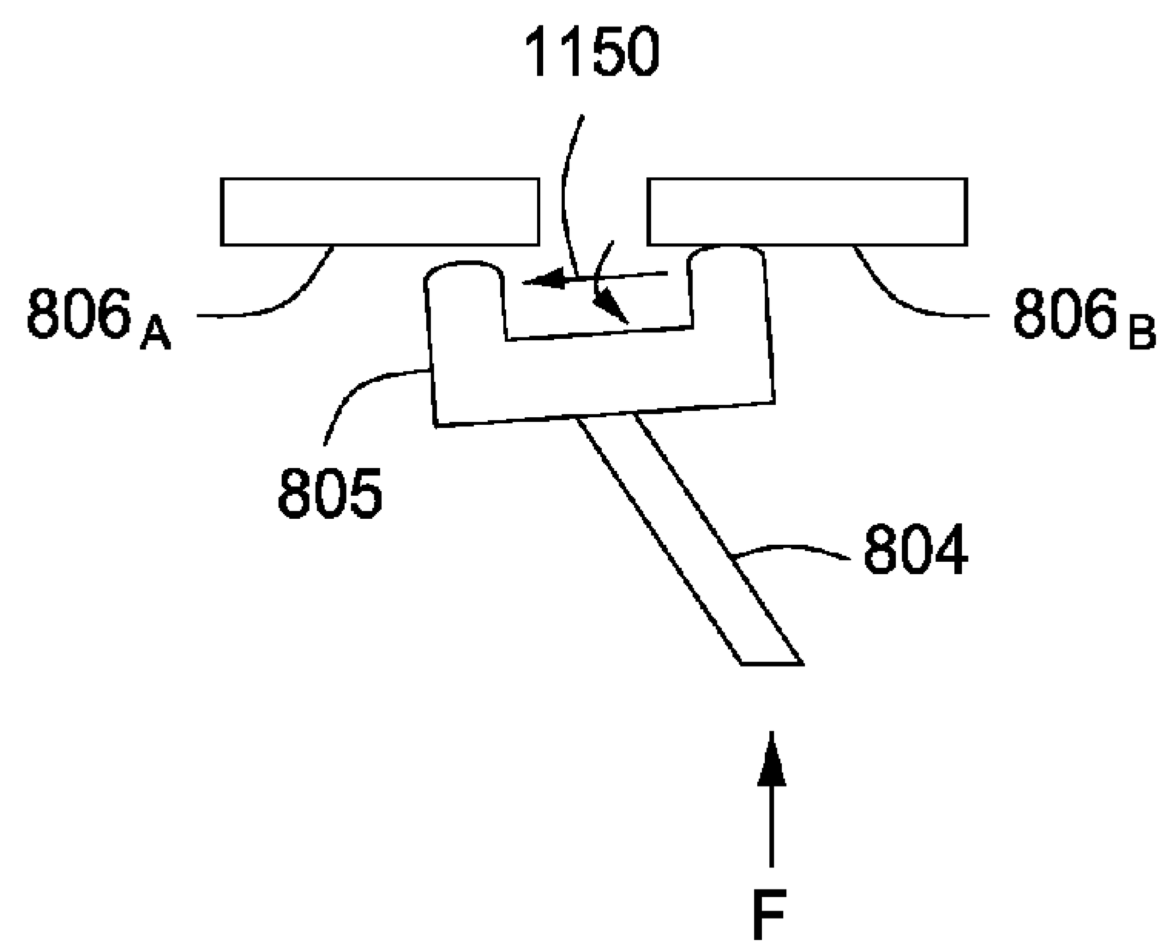


FIG. 11B

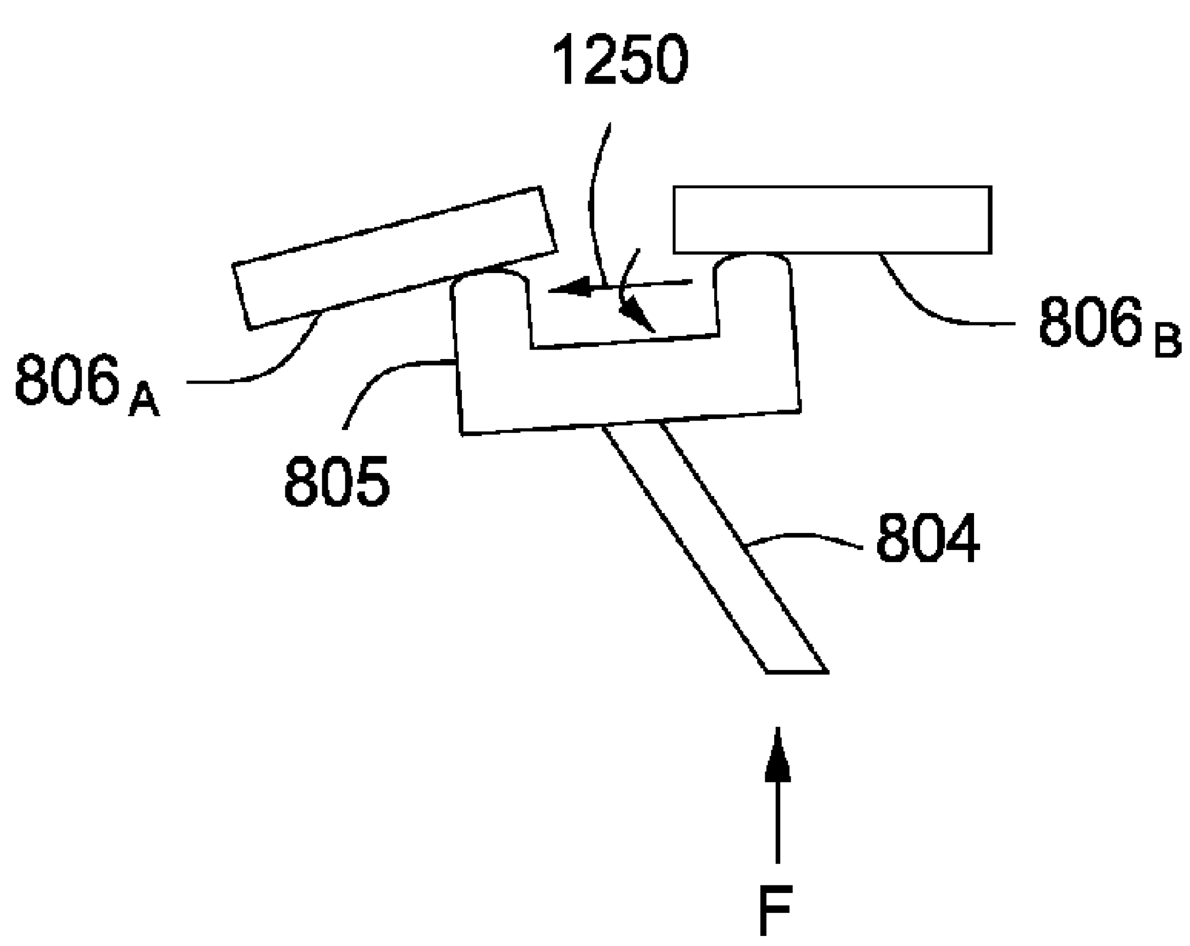


FIG. 12A

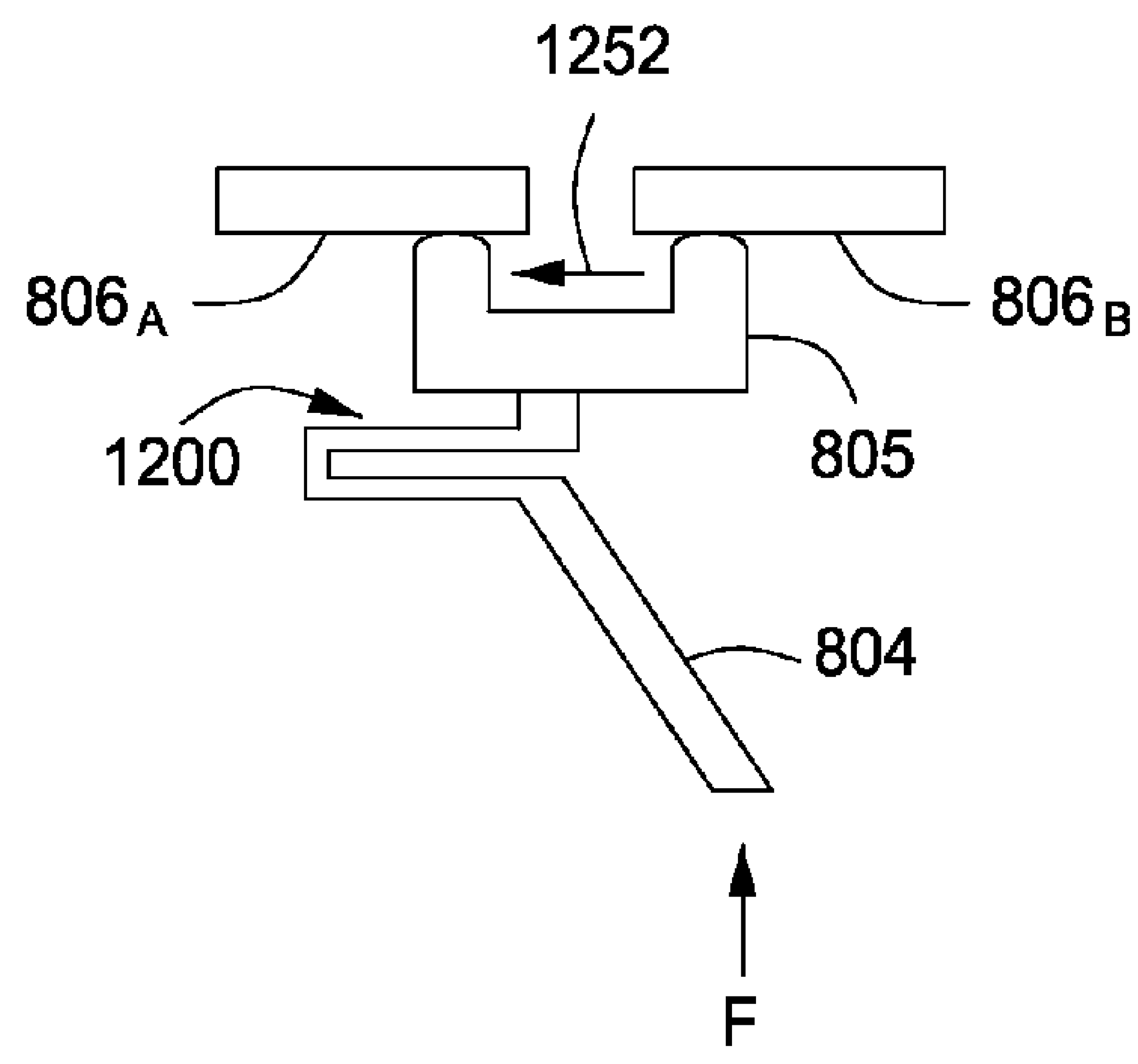
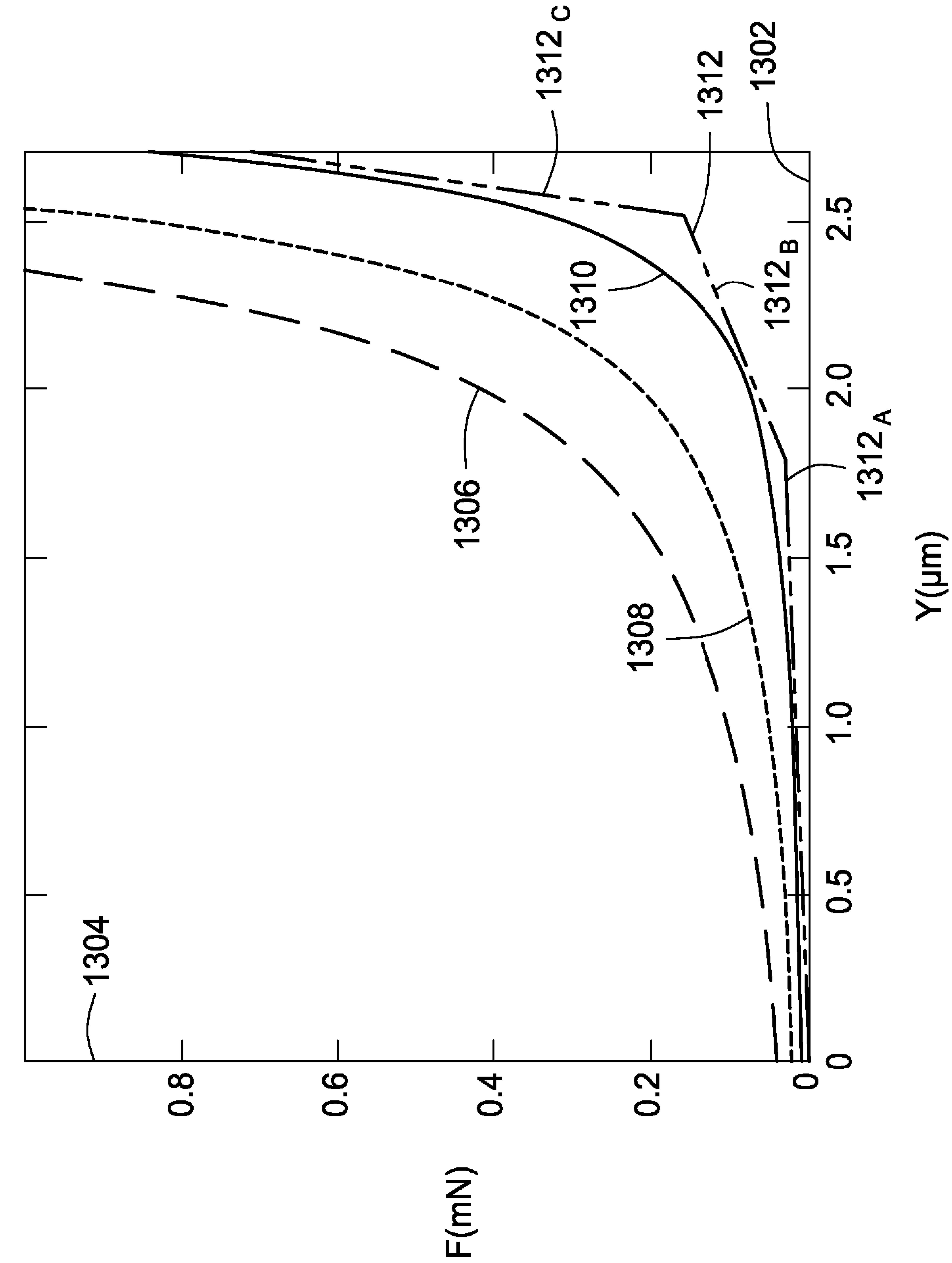


FIG. 12B


F(mN)
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0.6
0.4
0.2
0
Y(μm)
0
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1.0
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1312 C
1312 B
1312 A

FIG. 13

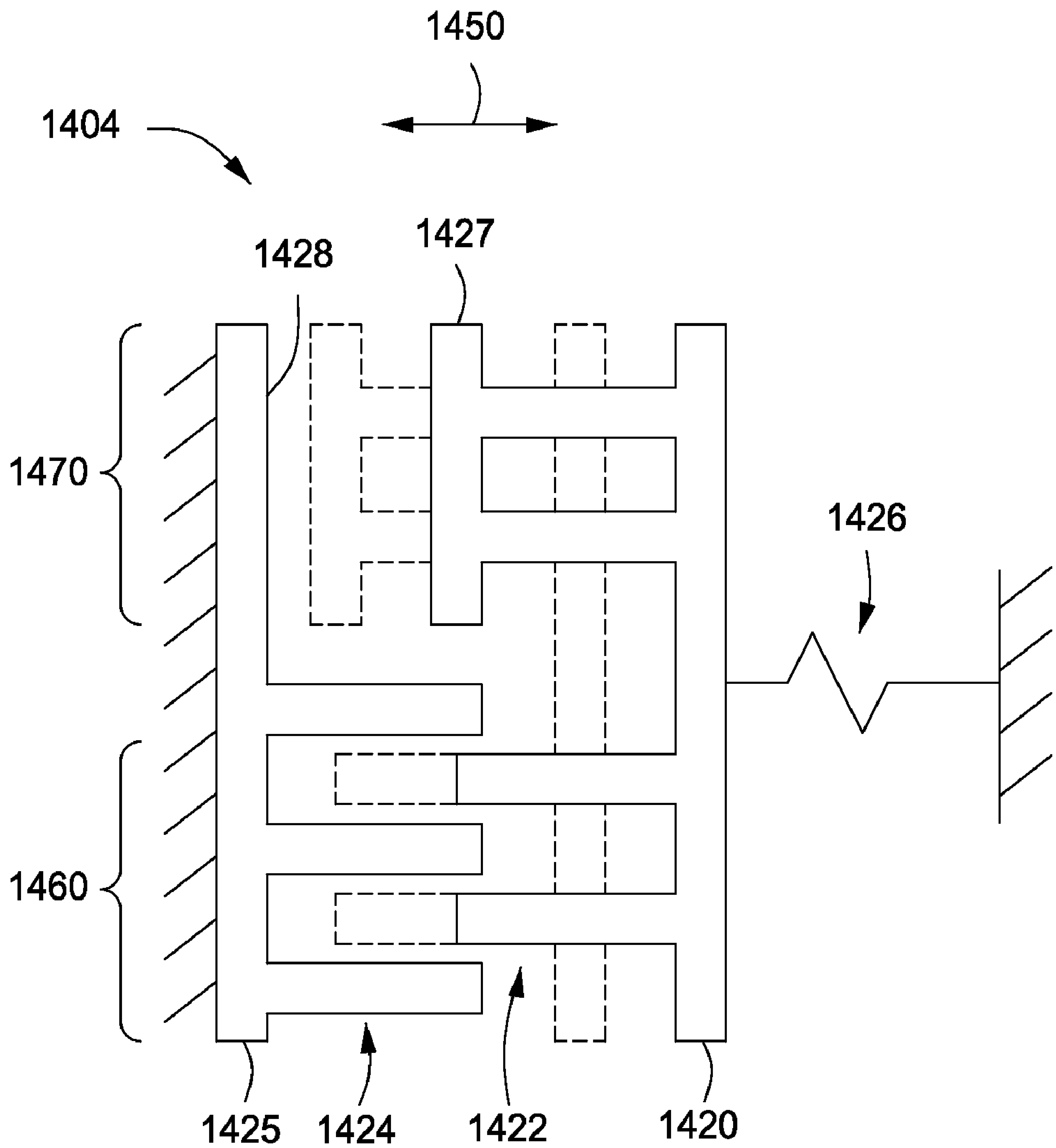

FIG. 14

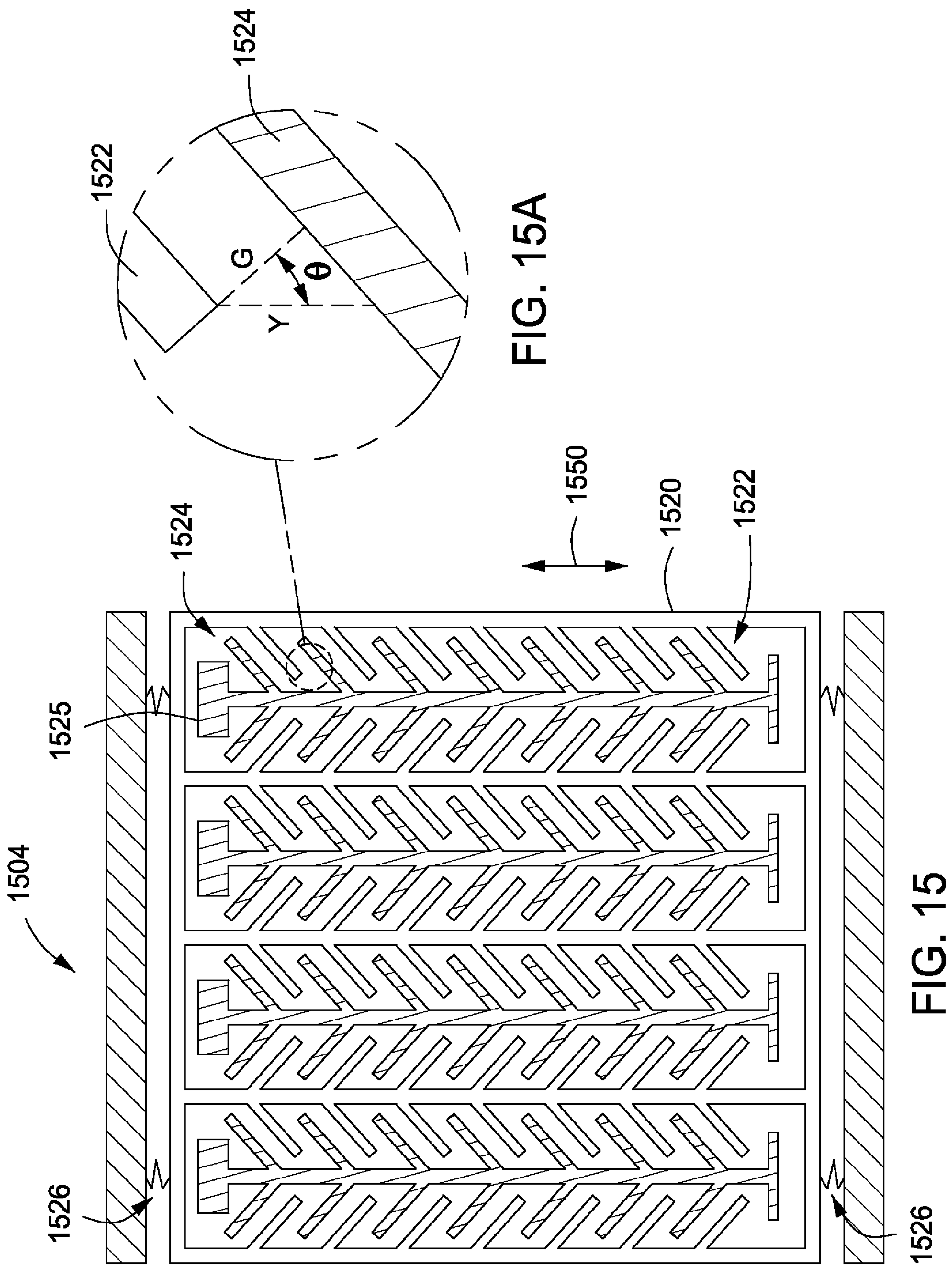

FIG. 15A

FIG. 15

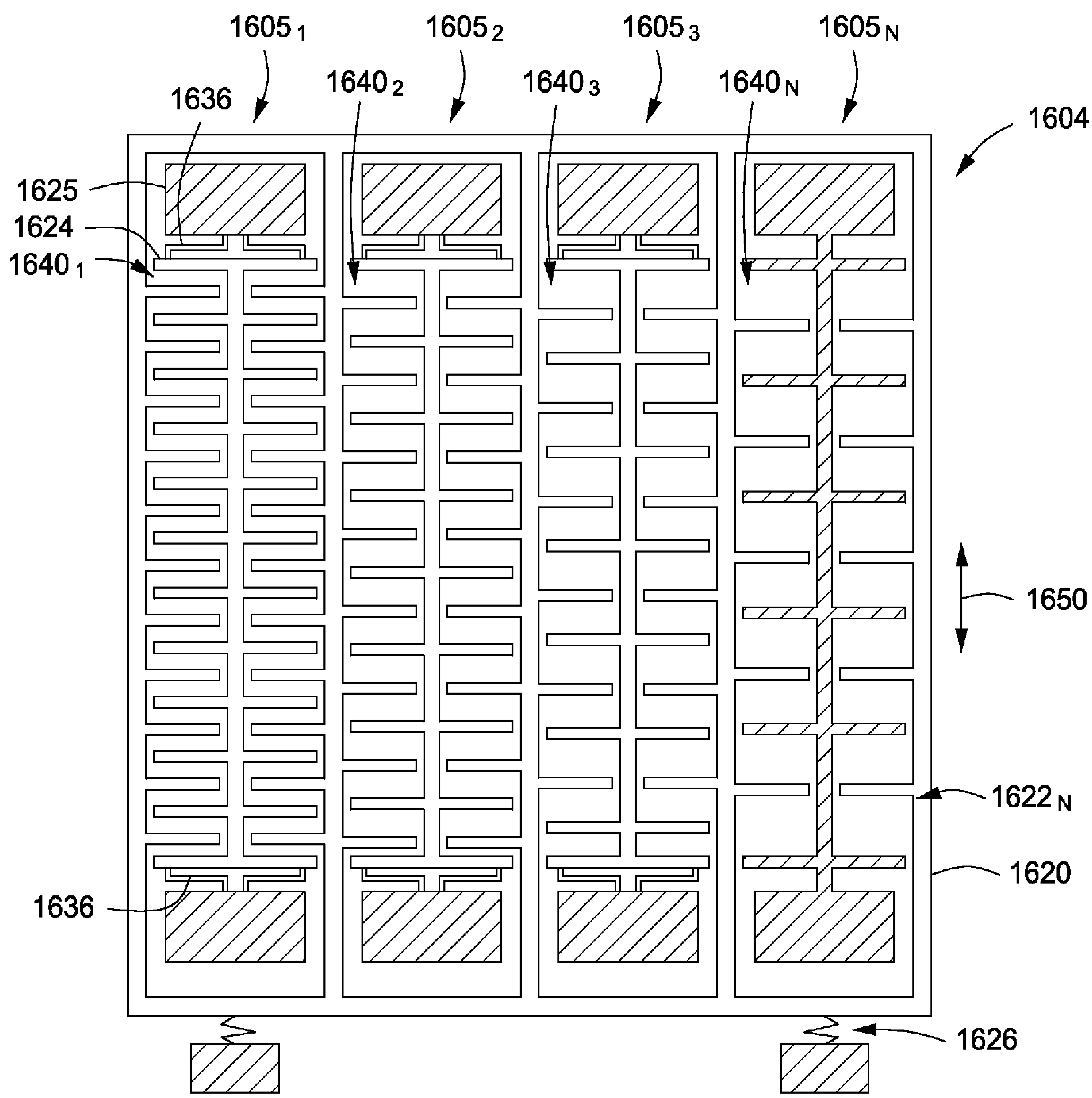
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FIG. 16

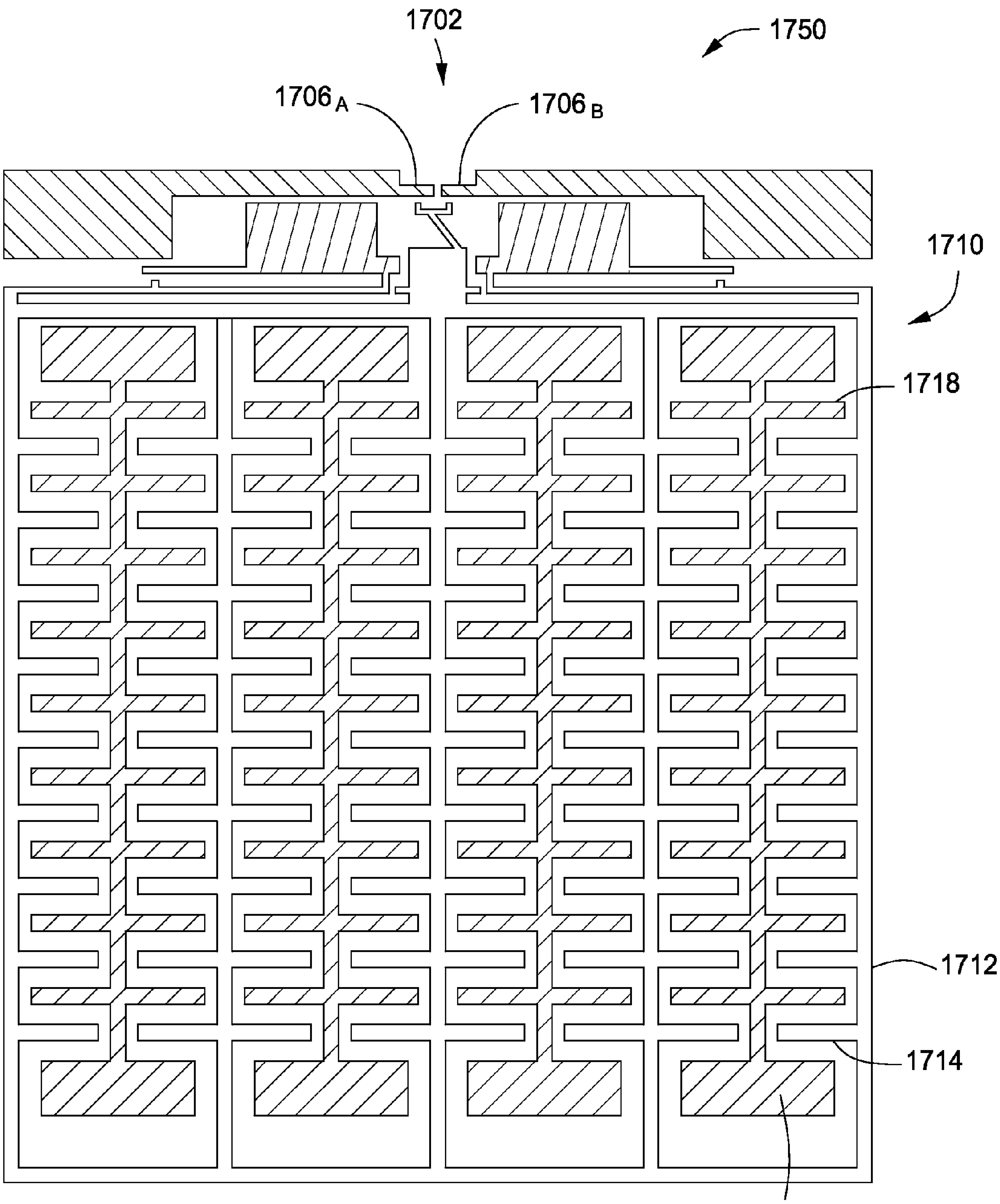

FIG. 17

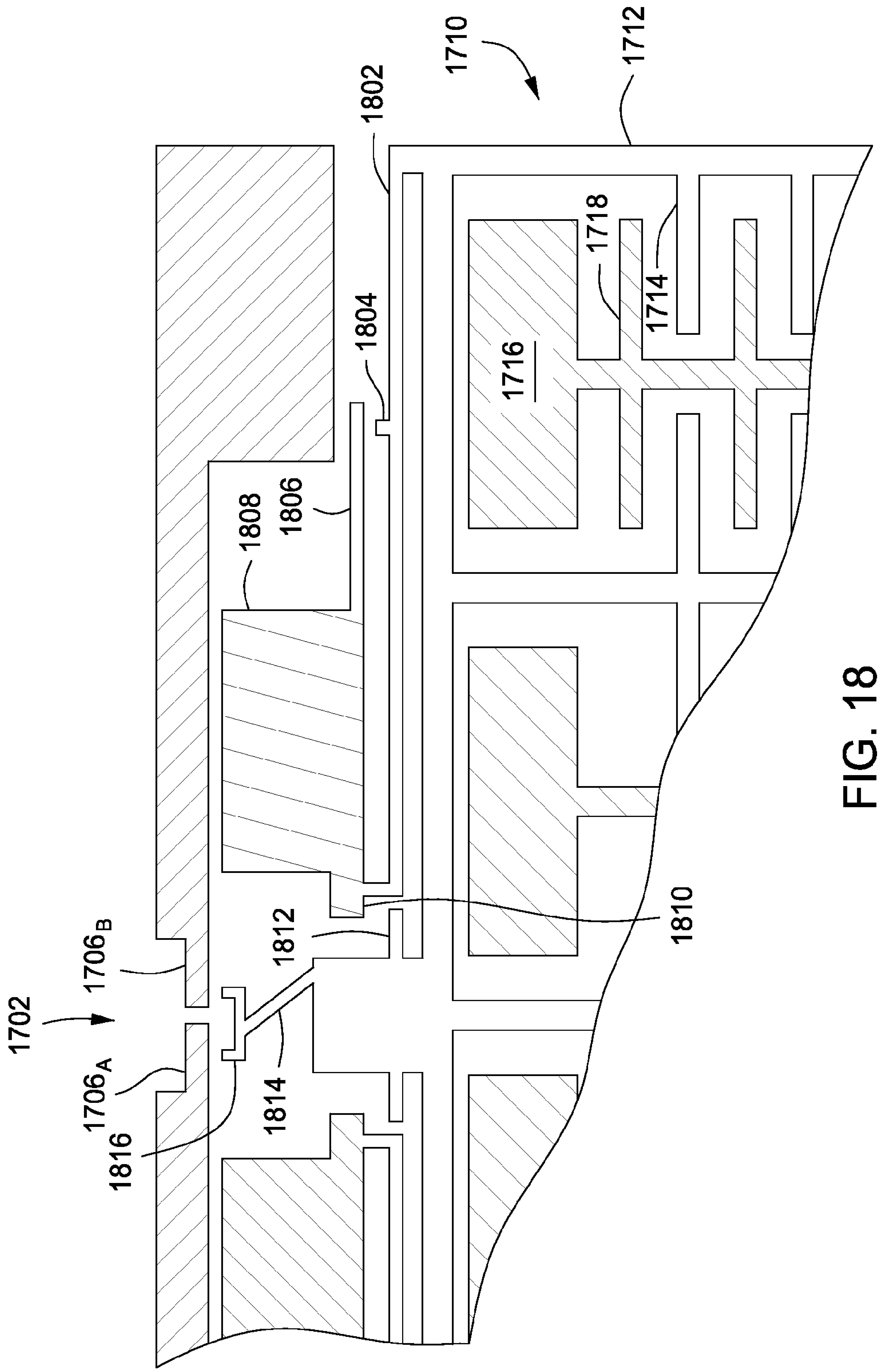
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FIG. 18

SWITCH FOR USE IN MICROELECTROMECHANICAL SYSTEMS (MEMS) AND MEMS DEVICES INCORPORATING SAME

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention generally relates to microelectromechanical systems (MEMS), and more particularly, to switches used in MEMS devices.

2. Description of the Related Art

Many systems, such as semiconductor testing systems, electronic circuits, microelectromechanical systems (MEMS), or the like (as non-limiting examples), often utilize switches to selectively make contacts to route electrical signals through the systems to facilitate the use and/or control thereof. Such switches are typically expected to have a fixed lifetime, such that any problem that interferes with the operation or performance of the switch typically effectively destroys the system. For example, the electrical performance of the switch may be degraded due to oxidation of the contacts of the switch. In addition, contact pad wear due to switch operation may also degrade the performance and/or the life of the switch. Further, particles or other contaminants may also interfere with switch performance.

Thus, there is a need for an improved switch for such systems.

SUMMARY OF THE INVENTION

Embodiments of the present invention provide microelectromechanical systems (MEMS) switching methods and apparatus having improved performance and lifetime as compared to conventional MEMS switches. In some embodiments, a MEMS switch may include a resilient contact element comprising a beam and a tip configured to wipe (i.e., providing a wiping motion across) a contact surface; and a MEMS actuator having an open position that maintains the tip and the contact surface in a spaced apart relation and a closed position that brings the tip into contact with the contact surface, wherein the resilient contact element and the MEMS actuator are disposed on a substrate and are movable in a plane substantially parallel to the substrate. In some embodiments, various contact elements are provided for the MEMS switch. In some embodiments, various actuators are provided for control of the operation of the MEMS switch.

In some embodiments, a MEMS switch may include a resilient contact element comprising a beam flexible about a pivot point and having a tip disposed proximate an end of the beam and configured to engage a contact surface; and a MEMS actuator coupled to the resilient contact element and having an open position that maintains the tip and the contact surface in a spaced apart relation and a closed position that brings the tip into contact with the contact surface, wherein the actuator is coupled to the beam at a point remote from the pivot point.

In some embodiments, various multi-stage spring systems are provided herein. In some embodiments, a multi-stage spring system includes a spring assembly having at least one resilient element; and a tip coupled to the spring assembly and configured to wipe a contact surface upon continued deflection of the spring assembly after initial contact with the contact surface; wherein the spring assembly has a first spring constant when deflected up to a first distance, a greater, second spring constant when deflected beyond the first distance and up to a second distance, and a greater, third spring constant when deflected beyond the second distance and up to a third distance, and wherein the spring assembly stores mechanical energy when deflected towards the contact surface that biases the spring assembly away from the contact surface when released.

In some embodiments, a MEMS actuator may include a comb actuator movable between a first position and a second position; and a gap closing actuator coupled to the comb actuator, wherein opposing electrodes of the gap closing actuator are brought into operable proximity to each other when the comb actuator is in the second position.

In some embodiments, a MEMS actuator may include a gap closing actuator having a plurality of first electrodes and a plurality of second electrodes disposed parallel to the first electrodes and linearly movable in a non-normal and non-parallel direction with respect thereto.

In some embodiments, a MEMS actuator may include a first gap closing actuator comprising a first plurality of electrodes having a first gap disposed therebetween; and a second gap closing actuator comprising a second plurality of electrodes having a second gap disposed therebetween, the first gap closing actuator coupled to the second gap closing actuator such that the closing of the first gap partially closes the second gap.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which features of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

FIG. **1** depicts a schematic diagram of a MEMS switch in accordance with some embodiments of the present invention.

FIG. **2** depicts a schematic diagram of a MEMS switch in accordance with some embodiments of the present invention.

FIGS. **3**A-C depict non-limiting examples of springs suitable for use in MEMS switches in accordance with some embodiments of the invention.

FIG. **4** depicts a schematic diagram of a MEMS switch in accordance with some embodiments of the present invention.

FIGS. **5** and **5**A respectively depict depicts a schematic diagram of a MEMS switch in accordance with some embodiments of the present invention and a partial detail view thereof.

FIG. **6** depicts a schematic diagram of a MEMS switch in accordance with some embodiments of the present invention.

FIG. **7** depicts a schematic diagram of a MEMS switch in accordance with some embodiments of the present invention.

FIGS. **8**A-C depict schematic diagrams of multi-stage springs in accordance with some embodiments of the present invention and suitable for use in a MEMS switch in accordance with some embodiments of the invention.

FIGS. **9**A-B depict non-limiting examples of contacts suitable for use with multi-stage springs in accordance with some embodiments of the invention.

FIGS. **10**A-C depict non-limiting examples of tips suitable for use with multi-stage springs in accordance with some embodiments of the invention.

FIGS. **11**A-B depict stages of operation of a multi-stage spring having a tip configuration in accordance with some embodiments of the present invention.

FIGS. **12**A-B respectively depict various tip configurations of a multi-stage spring in accordance with some embodiments of the present invention.

FIG. **13** depicts a graph showing force versus distance traveled for a multi-stage spring in accordance with some embodiments of the invention.

FIG. **14** depicts an actuator suitable for use in MEMS switches in accordance with some embodiments of the invention.

FIGS. **15-15**A respectively depict an actuator suitable for use in MEMS switches in accordance with some embodiments of the invention and a partial detail thereof.

FIG. **16** depicts an actuator suitable for use in MEMS switches in accordance with some embodiments of the invention.

FIG. **17** depicts a schematic diagram of a MEMS switch having a multi-stage spring in accordance with some embodiments of the present invention.

FIG. **18** depicts a close up of portions of the multi-stage spring of FIG. **18**.

FIG. **19** depicts an electronic device having a MEMS switch in accordance with some embodiments of the present invention.

Where possible, identical reference numerals are used herein to designate elements that are common to the figures. The images used in the drawings may be simplified for illustrative purposes and are not necessarily depicted to scale.

DETAILED DESCRIPTION

This specification describes exemplary embodiments and applications of the invention. The invention, however, is not limited to these exemplary embodiments and applications or to the manner in which the exemplary embodiments and applications operate or are described herein. In addition, as the terms "on" and "attached to" are used herein, one object (e.g., a material, a layer, a substrate, etc.) can be "on" or "attached to" another object regardless of whether the one object is directly on or attached to the other object or there are one or more intervening objects between the one object and the other object. Also, directions (e.g., above, below, top, bottom, side, up, down, "x," "y," "z," etc.), if provided, are relative and provided solely by way of example and for ease of illustration and discussion and not by way of limitation. In addition, where reference is made to a list of elements (e.g., elements a, b, c), such reference is intended to include any one or more of the listed elements by itself or in any combination. Moreover, the terms "open" and "closed" or an "open position" and a "closed position" as used herein with respect to actuator positions or states are illustrative and generally may be considered a "first position" and a "second position," respectively, and should not be confused with the open or closed state of a switch to which the actuator may be coupled.

I. General Discussion

Embodiments of the present invention provide microelectromechanical systems (MEMS) switching methods and apparatus which can have improved performance and lifetime as compared to conventional MEMS switches. In some embodiments, the switch may be utilized in MEMS radio frequency (RF) switching applications. Embodiments of the present inventive MEMS switches may include various wipe-inducing contact elements that may provide improved electrical contact, signal quality, switch lifetime, reduced contact stiction, and/or other benefits as described below. Embodiments of the inventive MEMS switches may include various MEMS actuating mechanisms for inducing the movement of the switch that may provide greater force application, low voltage operational requirements (such as less than or equal to about 3 Volts), and/or other benefits as described below.

The inventive MEMS switch generally includes a contact element configured to make selective contact with one or more contact pads and an actuating mechanism for controlling the operation of the switch. For example, FIG. **1** depicts a MEMS switch **100** in accordance with some embodiments of the invention. The switch **100** may include a contact element **102** coupled to an actuator **104**, as shown schematically by a link **106**. The actuator **104** controls the motion of the contact element **102** in at least a direction towards and away from one or more contact pads for selectively opening and closing the switch **100**, as depicted by arrows **108**.

For example, as schematically shown in FIG. **1**, a signal path **112** having a contact pad **113** and a signal path **114** having a contact pad **115** may be disposed proximate the contact element **102** in a normally open configuration, such that when the contact element **102** moves towards (e.g., when deflected by the actuator **104**) and comes into contact with the respective contact pads **113**, **115** of the paths **112**, **114**, the switch **100** may be closed. Such signal paths may generally be any electrical signal path. In some embodiments, the signal paths may be RF signal paths. Although shown as coupled to the contact element **102**, the actuator **104** may be separate from the contact element **102** and may be configured to selectively engage the contact element **102** during operation of the switch (as described in more detail below in FIG. **2**).

In some embodiments, the actuator **104** may deflect the contact element **102** in a direction away from the actuator and towards one or more contacts to be made by the switch (e.g., contact pads **113**, **115**). In some embodiments, actuation of the actuator **104** (e.g., moving from an initial position to a second position that deflects the contact element towards the contact pads **113**, **115**) may generate a restoring force biased away from the direction of movement of the actuator **104** that may facilitate returning the actuator **104** (and the contact element **102**) to its initial position.

In some embodiments, the contact element **102** may also provide a motion at least partially laterally with respect to the contact pads **113**, **115**, as depicted by arrows **110**. Such lateral motion of the contact element **102** may advantageously provide for a physical wipe of the contact pads **113**, **115** by the contact element **102**, thereby facilitating breaking through any oxide layer, particles, or other contamination that may be present between the contact element **102** and the contact pads **113**, **115**. In some embodiments, the contact element **102** may store mechanical energy upon wiping the contact pads, thereby providing a restoring force (or an increased restoring force) that may facilitate overcoming any stiction that may develop between the contact element **102** and any of the contact pads **113**, **115** when the switch **100** is in the closed position. This restoring force may be independent of any restoring force that might be part of actuator **104**, or may work in combination with any restoring force present in actuator **104**.

In some embodiments, the switch **100** may comprise a wipe-capable switch. As used herein, the term "wipe capable" means that the switch **100** is configured to be able to wipe the contact pad (e.g., either or both of **113**, **115**) upon closing the switch **100**. Such wipe may be provided selectively (e.g., the switch may be capable of closing with or without providing wipe) or each time the switch is closed. In addition, the magnitude of any wipe provided may be controlled such that the distance that the tip moves with respect to the contact pads after initial contact may be controlled as desired. The term "wipe" may be defined as lateral movement of the contact element of the switch across the contact pad after initial contact with the contact pad (e.g., the contact element of the switch initially contacts the contact pad at a first point, then wipes the surface of the contact pad as it moves to a second point). Thus, the term "wipe" includes any post-contact motion between contact elements and contact pads such that physical, frictional relative motion therebetween is developed. As used herein, the term "contact" includes any initial contact sufficient to establish electrical connection between contact elements and contact pads and any additional motion of either or both of contact elements and contact pads sufficient to induce wipe therebetween.

In some embodiments, any of the switches disclosed herein may be configured in plane substantially parallel to a substrate upon which the switch may be disposed. For example, each of the views of switches, or portions thereof (such as contact elements, springs, actuators, or the like), shown in the Figures contained herein may be top views of the respective components (or portions thereof) such that a substrate upon which the switch is disposed lies beneath the components illustrated in the various drawings. As such, the actuation of the switch (for example, the movement of the actuator **104** and the contact element **102**, as shown in FIG. **1**) may be in a plane substantially parallel to the page as drawn, and to the underlying substrate. Such substrate-parallel configuration may provide additional flexibility in configuration of the various components comprising the switch (e.g., the actuator, contact elements, contact pads on the substrate, and the like) and/or improved performance as compared to substrate-perpendicular configurations (e.g., where the contact elements of the switch move primarily perpendicularly with respect to an underlying substrate upon which the contact pads are disposed).

Various embodiments of MEMS switches in accordance with the teachings of the present invention as disclosed herein are contemplated. Additionally, it is contemplated that one or more features of each of the embodiments disclosed herein may be combined with one or more features of any other embodiments provided to the extent not inconsistent with the present teachings.

FIG. **2** depicts one illustrative example of a MEMS switch **200** in accordance with some embodiments of the invention. The switch **200** is generally similar to the switch **100** described above and embodies some of the many variations contemplated. The switch **200** may be fabricated using simple, low-cost techniques and may be lithographically fabricated on a common substrate. As discussed above, the switch **200** can be fabricated in a plane generally parallel to the underlying substrate.

The switch **200** can include a contact element **202** and an actuator **204** configured to selectively control the position of the switch **200** from a first position to a second position (corresponding to, for example, open or closed positions of the switch, or vice versa). In some embodiments, the contact element **202** may comprise a pair of resilient contact elements $\mathbf{202}_A$ and $\mathbf{202}_B$. In some embodiments, the contact element **202** (or contact elements $\mathbf{202}_A$ and $\mathbf{202}_B$) may include a resilient beam **216** having a tip **218** disposed at an end thereof. In some embodiments, and as depicted in FIG. **2**, the contact element **202** (or elements $\mathbf{202}_A$ and $\mathbf{202}_B$) may be coupled to signal paths **212**, **214** (for example at an end of the resilient beam **216** opposite the tip **218**) and disposed in a normally spaced apart relation with the actuator **204**.

The actuator **204** may have one or more contact pads **206** for selectively making contact with respective tips of the contact element **202** (or elements $\mathbf{202}_A$ and $\mathbf{202}_B$). In some embodiments, the contact pads **206** may be disposed at a non-parallel angle with respect to the contact element **202** (or elements $\mathbf{202}_A$ and $\mathbf{202}_B$) to facilitate inducing wipe upon contact therebetween. In some embodiments, the contact pads **206** may be disposed non-parallel (e.g., at an angle) to the contact element **202** (or elements $\mathbf{202}_A$ and $\mathbf{202}_B$) such that wipe may be developed through configuration of the contact element **202** (or elements $\mathbf{202}_A$ and $\mathbf{202}_B$). For example, when resilient beam **216** is deflected (e.g., upward in reference to the drawing), such movement will cause the elements $\mathbf{202}_A$ and $\mathbf{202}_B$ to wipe the contact pads **206**.

The actuator **204** may comprise any suitable actuator, including but not limited to any of the actuators described in more detail below. In some embodiments, the actuator **204** may comprise an electrostatic gap closing actuator. For example, as depicted in FIG. **2**, the actuator **204** includes a movable frame **220** that supports a plurality of movable electrodes **222** proximate a mating plurality of fixed electrodes **224**. The frame **220** is movable between a first, resting position (normally open as shown in FIG. **2**) and a second, actuated position (a closed position, or up the page, as shown in FIG. **2** and denoted by arrows **250**). One or more springs may be provided in the actuator **204** to facilitate returning the frame **220** to the resting position. For example, a plurality of shuttle springs **226** and bumpers **228** may be provided to store mechanical energy upon actuation of the actuator **204**. In some embodiments, the shuttle springs **226** may be coupled to a fixed structure **230** to provide a support and fixed frame of reference for the shuttle springs **226** and the movable frame **220**.

To facilitate generating an electrostatic attractive force between the fixed and movable electrodes **224**, **222**, one of the fixed or movable electrodes **224**, **222** is generally grounded and the other coupled to a power source for selectively providing a voltage thereto. Thus, the potential difference between the powered and grounded electrodes develops an electrostatic attractive force therebetween, and causing the movable electrodes **222** to move towards the fixed electrodes **224**. In the embodiment depicted in FIG. **2**, the movable electrode **222** may be grounded, for example, by a ground connection made to the fixed structure **230**. The fixed electrodes **224** may be powered, for example, through a plurality of connections (such as wire bonds **232**) made to a bus **234** or other element to which a connection may be made to the power source (not shown).

In operation, the force generated by the actuator **204** is a function of the voltage applied, the distance, or gap, between the respective fixed and movable electrodes **224**, **222**, and the surface area over which the electrostatic potential develops (e.g., the mating surface area of the opposing electrodes times the number of pairs of electrodes provided). Although one geometry is shown in FIG. **2** having four rows of a given number of electrodes, it is contemplated that one or more rows of electrodes may be provided of varying size and number, and that the mating electrodes need not be provided in rows, that multiple rows or sets of mating electrodes need not have the same configuration as each other, or the like.

II. Contact Element Examples

Embodiments of the present invention may utilize a variety of contact element configurations. Such contact elements may have any suitable form for generating or providing a wiping action during use. For example, the contact element can include a beam having a first end configured with a tip for contacting the surface of a contact pad and a second end configured to be attached to a supporting substrate (not shown).

The beam, or portions thereof, may comprise one or more layers and may comprise one or more electrically conductive, semiconductive, and/or nonconductive materials. Examples of suitable conductive materials include metals. In some embodiments, the beam may comprise nickel, copper, cobalt, iron, gold, silver, elements of the platinum group, noble metals, semi-noble metals, elements of the palladium group, tungsten, molybdenum, beryllium, and the like, and alloys thereof (such as, but not limited to, nickel-cobalt alloys, copper-beryllium alloys, or the like). Examples of non-conductive materials include silicon dioxide. Examples of semiconductive materials include silicon.

The tip may be formed integrally with the beam or may comprise a separate layer or layers. In some embodiments, the tip may be fabricated from any of the above materials. In some embodiments, the tip may be fabricated from noble metals and semi-noble metals, such as palladium, gold, rhodium, and combinations or alloys thereof (such as palladium-cobalt alloys, nickel-palladium alloys, or the like), and the like.

The contact pad may generally be fabricated, at least in part, from any suitable electrically conductive material. Examples of such materials may include any of the conductive materials discussed above with respect to the beam and the tip of the contact element. Although examples of specific materials for the beam and tip of the contact element and the contact pad of the switch are provided herein, the specific materials are not intended to be limited by such examples and any suitable materials for providing the function of the contact element and/or the contact pad in accordance with the teachings provided herein are contemplated.

The contact element typically has a spring constant and yield strength suitable for developing sufficient contact force when contacting a contact pad (e.g., sufficient to break through an oxide layer on the surface of the contact pad and/or sufficient to provide a reliable temporary pressure contact suitable for transmission of an electric signal therebetween) for repeated temporary contacting of the contact elements without permanent deformation thereof. It is contemplated that the contact element may have a suitable spring constant or constants for various applications where particular contact forces are required to establish reliable temporary electrical contact with the contact pad without damaging either the resilient contact element or the contact pad.

For example, FIGS. **3**A-C depict a few non-limiting examples of the many embodiments of contact elements suitable for use in MEMS switches as described herein. In some embodiments, as depicted in FIG. **3**A, the contact element **102** may include a resilient beam **316** having a tip **318** disposed at an end thereof. The tip **318** may be configured to contact a contact pad of a MEMS switch directly, or may include a contact **319** suitable for contacting the contact pad.

The beam **316** may be linear, as shown in FIG. **3**A, or in some embodiments and as depicted in FIG. **3**B, the beam **316** may be non-linear. In some embodiments and as depicted in FIG. **3**C, the contact element **102** may include a reinforcement member **317** may be coupled to the resilient beam **316**C. In some embodiments, the reinforcement member **317** may be coupled to the resilient beam **316**C via a bonding layer **330** (such as an adhesive, or the like). Alternatively, the reinforcement member **317** may be fabricated integrally with the resilient beam **316**C. In some embodiments, the reinforcement member **317** and the resilient beam **316**C may be configured in a box spring configuration. Alternatively, a resilient portion **332** may be provided in the reinforcement member **317**. The resilient portion **332** may provide a torsional spring effect.

Examples of additional suitable spring configurations that may be found in commonly assigned U.S. patent application Ser. No. 11/611,874, filed Dec. 17, 2006, and entitled, "Reinforced Contact Elements," Ser. No. 11/617,373, filed Dec. 28, 2006, and entitled, "Resilient Contact Elements and Methods of Fabrication," Ser. No. 11/617,394, filed Dec. 28, 2006, and entitled, "Rotating Contact Element and Methods of Fabrication," and Ser. No. 11/862,172, filed Sep. 26, 2007, and entitled, "Reduced Scrub Contact Element."

Some actuators, for example electrostatic gap closing actuators, may provide relatively small ranges of motion. Accordingly, a contact element configuration may be provided that can amplify the range of motion provided by the actuator to obtain greater range of motion of the tip of the contact element. The increased range of motion may provide greater flexibility in design of the switch, may enable the switch to possess greater wipe for a given actuation voltage, as compared to conventional designs, or the like.

For example, FIG. **4** depicts an illustrative example of a MEMS switch **400** in accordance with some embodiments of the invention. The switch **400** is generally similar to the switch **100** described above and embodies some of the many variations contemplated herein. The switch **400** may include a contact element **402** constrained about a pivot point **410** and coupled to an actuator **404**. The contact element **402** may include a beam **416** having a tip **418** disposed at one end of the beam **416**. The beam **416** may be constrained at the pivot point **410**, such as by providing a flexible connection **430** extending from an anchor, or fixed structure **432**, to a particular location on the beam **416**. The tip **418** is generally configured to make temporary electrical contact with contact pads provided, for example, along signal path **412** and signal path **414**, to selectively close and open the switch **400** as desired during operation. The tip **418** may have a contact **420** disposed thereon suitable for contacting the contact pads, similar to the contact **319** discussed above with respect to FIGS. **3**A-C.

The actuator **404** may be coupled to the contact element **402** at a point along the beam **416** on a side opposite the tip **418** with respect to the pivot point **410**. The actuator **404** may be coupled to the beam **416**, for example, by a structural element **406**. The relative positions of the connection to the actuator and the pivot point and the tip along the beam, divides the beam into a first length L_1 measured between the tip **418** and the pivot point **410**, and a second length L_2 measured between the pivot point **410** and the connection of the structural element **406**. The relative dimensions of the lengths L_1, L_2, may be controlled to determine the amplification of the movement of the actuator **404** during operation.

For example, although shown as having the actuator **404** coupled to the shorter side of the beam **416**, in some embodiments, the pivot point **410** may be positioned such that the actuator **404** may be coupled to the longer side of the beam **416**. The mechanical advantage provided by the longer arm of the beam **416** relative to the pivot point **410** facilitates generating a larger actuation force on the switch contact (e.g., contact pads on signal paths **412**, **414**) with smaller forces generated by the actuator **404**. Accordingly, a large motion, small force actuator (such as an electrostatic comb actuator, or the like) may be coupled to the beam **416**.

In addition to configurations such as described above with respect to FIG. **4**, wherein movement of the actuator selectively closes the RF switch **400** (e.g., a normally open switch), embodiments are contemplated wherein a normally closed switch may be provided. For example, in some embodiments, and as shown in FIG. **5**, a normally closed switch **500** is depicted having a beam **502** coupled to an actuator **504** via a structural element **506**. A tip **518** may be disposed at one end of the beam **516** and may be normally disposed in contact with contact pads proximate respective ends of a signal path **512** and a signal path **514**. Optionally, a contact **520** may be provided at the end of the tip **518** for making contact with the contact pads on the signal paths **512**, **514**. In some embodiments, the actuator **504** may be coupled to the beam **516** at a point disposed along the beam **516** between a pivot point **510** and the tip **518**. A fixed structure **532** may be provided having a flexible extension **530** coupled to the beam **516** to provide a pivot point **510** about which the beam **516** may flex.

In some embodiments, a mechanism may be provided, such as locking element **534**, to maintain the switch **500** in a normally closed position. As shown in FIG. **5**A, in some embodiments, the locking element **534** may comprise a flexure **538** extending from the anchor structure **532** having a tip **536** and a locking feature **540** formed thereon. A mating flexible locking feature **542** may be provided via a flexure **544** extending from a portion of the fixed structure **532**, or some other fixed structure, that meets with the locking structure **540** formed on the tip **536**. The tip **536** may be formed to correspond with the switch **500** being in a normally open position (as shown in dotted lines at **546**). The locking element **534** may be engaged by pushing the tip **536** forward to engage the locking features **540**, **542** and retain the tip **534** in a forward position, whereby the tip **536** pushes the beam **516** to maintain a normally closed position.

The above configurations as shown in FIG. **4** and FIG. **5** depict only some of the many variations of using anchored, pivoting beams coupled to an actuator for amplifying the movement of a tip of a contact element. Many other geometries and configurations may also be provided within the scope of embodiments of the present invention. For example, as shown in FIG. **6**, a contact element **602** may be provided having dual beams **616_A** and **616_B** coupled together by a flexure **617** and respectively anchored at fixed structures **632_A** and **632_B** to an actuator **604**. A tip **618** may be provided at an end of the beam **616_A**. In operation, the movement of the actuator **604** (e.g., downward on the page, as illustratively shown with respect to FIG. **6**) applies a force on beam **616_B** which, in turn, applies a force to one end of the beam **616_A** via the flexure **617**, causing the beam **616_A** to rotate about the pivot point **610**, thereby causing the tip **618** and/or contact **620** to come into contact with contacts along signal paths **612** and **614**. Although sown in one particular configuration, any actuator could be used in place of actuator **604**, it is sufficient that the actuator cause the movement of **616_B** from a first position to the second position.

In addition to the various embodiments described above with respect to FIGS. **4** through **6**, various configurations of the switch may be provided for opening and closing multiple switches or providing control over multiple switches with a single actuator. For example, FIG. **7** depicts a single-pole, double-throw switch **700** generally similar to switch **400** as described above with respect to FIG. **4**. However, the actuator is coupled to two beams **716**A and **716**B via a flexure **717** to allow for simultaneous control over switches **702**A and **702**B.

Embodiments of the present invention further may include multi-stage spring systems that provide variable spring compliance to shape the mechanical characteristics of the spring system. Such multi-stage spring systems may advantageously provide an increased restoring force for assisting in overcoming any contact stiction that may occur between the contacts that the switch engages upon closing as compared to conventional spring systems. For example, conventional spring systems are typically linear and have a k value that is low enough to accommodate the low electrostatic force that is initially generated when used with electrostatic actuators (e.g., to allow the switch to begin to close when the gap between the electrodes of the electrostatic actuator is large). In addition, such multi-stage systems may further facilitate storing restoring forces that may increase as a function of the reduction in the gap between electrodes of an electrostatic actuator (which increases the electrostatic force between the electrodes), thereby further facilitating overcoming any contact stiction that may develop between the electrodes and/or the contacts of the switch (as compared to conventional systems having low, constant mechanical restoring forces due to the linear spring resulting in lesser ability of contact-breaking for a MEMS switching device utilizing such conventional spring systems).

In some embodiments, the mechanical characteristics of the spring system may be shaped to conform to forces applied by an actuating means coupled to the multi-stage spring system. The multi-stage spring system may offer different compliant levels at different deflection locations. In a non-limiting example, the multi-stage spring system may be utilized to provide a compact, high-density, low-voltage MEMS switch. For example, the multi-stage spring system can be used as part of, or in conjunction with, a MEMS electrostatic actuator (such as the actuators disclosed herein) for various applications, including RF switches. In some embodiments, a MEMS switch may be formed using the multi-stage spring system as part of, or in conjunction with, a MEMS electrostatic actuator having movement parallel to the plane of a substrate on which the switch is disposed. The multi-stage spring system may advantageously provide higher contact-breaking forces as compared to conventional designs in such a MEMS switching device, or other applications as well.

The multi-stage spring systems disclosed herein may sometimes be referred to as multi-stage springs or multi-stage spring assemblies. In some embodiments, the multi-stage spring (or multi-stage spring assembly) may include a plurality of spring elements for providing varying spring constants (k values) corresponding to varying quantities, or distances, of deflection of the spring. As such, the multi-stage spring assembly may have a first spring constant when deflected up to a first distance (e.g., a first stage), a greater, second spring constant when deflected beyond the first distance and up to a second distance (e.g., a second stage), and a greater, third spring constant when deflected beyond the second distance and up to a third distance (e.g., a third stage), and so on for embodiments having greater numbers of spring elements or stages. Each individual stage of the multi-stage spring may have any desired k value such that the total k value at each stage and over the entire range of movement of the multi-stage spring may be controlled as desired. The multi-stage springs in accordance with the various embodiments disclosed herein may have greater or fewer spring elements than those illustratively shown.

FIG. **8**A depicts a schematic side view of a multi-stage spring **802**A in accordance with some embodiments in the present invention. In the embodiment depicted in FIG. **8**A, the multi-stage spring **802**A includes a first spring element **803**, a second spring element **808**, and a third spring element **804**. The spring elements may take any suitable form such as simple, or linear (e.g., such as second spring element **808**), complex, or non-linear (e.g., such as first spring element **803**), curved, combinations of the above, or the like. The spring elements may be anchored at any desired location (as illustratively shown by hash marks in FIG. **8**A at **812** and **814**) to provide the relative movement of the respective spring elements and the engagement thereof during operation.

The various spring elements (e.g., **803**, **804**, **808** in the embodiment depicted in FIG. **8**A) of the multi-stage spring may be configured to be at least partially sequentially engaged upon deflection of a first spring element in order to provide increasing k values for the multi-stage spring as a whole as the first spring element travels across an increasing range of deflection. The deflection of the respective spring elements may be controlled via application of a force (depicted in the Figures herein as an arrow labeled "F" for illustration) to the multi-stage spring. Such a force may be provided by single or composite sources (such as by one or more of the actuators described herein) and is only illustratively shown in the Figures. The force may be applied at any suitable location and in any suitable direction to provide the desired motion (e.g., deflection) of the respective spring elements of the multi-stage spring. For example, although shown in a single location in FIGS. **8**A-C, the force F may be applied at different locations, or at multiple locations, anywhere on the multi-stage spring to provide the desired motion of the respective spring elements of the multi-stage spring. The multi-stage spring assembly stores mechanical energy when deflected towards a contact surface that biases the spring assembly away from the contact surface when released.

For example, in some embodiments and as depicted in FIG. **8**A, the second spring element **808** may be configured to be engaged upon a desired quantity of deflection of the first spring element **803** (e.g., the force applied to the first spring element **803** may cause a downward deflection of the first spring element **803**, including at an end **820** of the first spring element **803**, thereby causing the first spring element **803** to contact the second spring element **808**). The second spring element **808** may have an extension **810** or other feature that engages the first spring element **803** after a desired quantity of deflection of the first spring element **803**. The extension **810**, or other feature, may be configured to define a small gap between the first spring element **803** and the second spring element **808** such that the second spring element **808** is engaged upon the desired quantity of deflection of the first spring element **803**. In operation, the first spring element **803** initially provides the multi-stage spring $\mathbf{802}_A$ with an initial k value (k**1**). Upon engaging the second spring element **808** (or the extension **810**), a second k value (k**2**) for the multi-stage spring $\mathbf{802}_A$ is provided. The second k value will be equal to an increased k value of the first spring element **803** (due to its effective shortening) plus the k value of the second spring element **808**.

The third spring element **804** may be configured to be engaged upon a second quantity of deflection of the first spring element **803** beyond the first quantity of deflection (e.g., after a desired quantity of deflection after engagement of the second spring element **808**). Thus, a third k value (k**3**) for the multi-stage spring $\mathbf{802}_A$ may be provided upon engagement of the third spring element **804**. Each spring element may be configured to provide an increase in the k value of the multi-stage spring as desired for a particular application (including greater of fewer stages, varying ranges of deflection for individual stages and/or for the multi-stage spring as a whole, or the like).

In some embodiments, the third spring element **804** may engage a contact surface of a member **806**. A portion of the third spring element **804** (or whichever final spring element ultimately engages the member **806**) may be configured to wipe the member **806**, as shown be arrows **850** (e.g., the portion of the third spring element **804** that contacts the member **806** may be configured to move with respect to the contact surface of the member **806** as the deflection increases and decreases to "wipe" the contact surface of the member **806**). The wiping, and subsequent unwiping motion upon retraction of the multi-stage spring $\mathbf{802}_A$, may facilitate overcoming any contact stiction between the member **806** and the portion of the third spring element **804** that contacts the member **806**. The wiping motion may further facilitate breaking through any oxide layer or particles or other contaminants that may exist between the member **806** and the portion of the third spring element **804** that contacts the member **806**, which may improve the operation of the switch (e.g., signal quality for electrical applications, switch lifetime, or the like).

In some embodiments, the spring element configured to wipe the member **106** may be angled with respect to the member **806** to provide the wipe. Although the third spring element **804** depicted in FIG. **8**A is shown at an about 45 degree angle with respect to the member **806**, other angles may be utilized to facilitate control of the k value provided by the spring element and/or control of the amount of travel of the spring element when deflected beyond initial contact with the member **806** (e.g., to control the amount of wipe provided).

In some embodiments, as shown in FIG. **8**A, the member **806** may be a separate component that is disposed with respect to the multi-stage spring $\mathbf{802}_A$ to facilitate contact of the third spring element **804** (or a subsequent spring in embodiments with greater numbers of spring elements) upon a desired quantity of deflection of the multi-stage spring $\mathbf{802}_A$. In some embodiments (not shown), the member **806** may be part of the multi-stage spring $\mathbf{802}_A$.

The quantity of deflection of the multi-stage spring $\mathbf{802}_A$, or of the first spring element **803**, may be controlled via application of a force (indicated by arrow F in FIG. **8**A) to deflect the first spring element **803**. The magnitude of the force applied may be selectively controlled to provide a desired quantity of deflection given the design of the multi-stage spring and the varying stages of k values provided by the multi-stage spring assembly as it deflects. The force may be applied via any suitable mechanism, such as an actuator. In some embodiments, the force may be applied by a MEMS actuator as discussed in more detail below. Although shown as being applied proximate a distal end of the first spring element **803**, the force may be applied at any suitable location of the multi-stage spring $\mathbf{802}_A$ for inducing deflection of the first spring element **803**.

Embodiments of the multi-stage spring disclosed herein may have various forms. For example, the number of spring elements and/or stages of the multi-stage spring may be selected as desired to control the k value of the multi-stage spring, and thereby to increase the stored mechanical energy upon deflection of the multi-stage spring. For example, FIG. **8**B illustrates embodiments of a multi-stage spring $\mathbf{802}_B$ wherein the spring elements have a different configuration. Specifically, as shown in FIG. **8**B, the first spring element **803** of the multi-stage spring $\mathbf{802}_B$ may be anchored at two points (**812**, **816**) and may be configured to deflect upon application of a force, F, to a central location (or any other suitable location or locations) on the first spring element **803**. A pair of second spring elements **808** may be provided to be engaged upon a desired quantity of deflection of the first spring element **803** (e.g., as respective ends **820**, **822** of the first spring element **803** deflect toward the second spring elements **808**). A third spring element **804** may be provided for being engaged upon a desired continued amount of deflection of the first spring element **803**. The configuration shown in FIGS. **8**A and **8**B are illustrative only and, as discussed above, many other configurations are contemplated.

In addition, the multi-stage spring may be utilized in various applications, such as electrical systems, mechanical systems, electromechanical systems, or the like. For example, a multi-stage spring in accordance with embodiments of the present invention may be utilized as a resilient contact element for making selective temporary electrical pressure contacts with a contact element. A non-limiting example of one such use may be illustrated using a multi-stage spring as shown in FIGS. **8**A-B, wherein the member **806** may provide a first conductive path and the first spring element **803** and the third spring element **804**, or portions thereof, may provide a second conductive path for making selective contact with the member **806** upon sufficient deflection of the first spring element **803** (and thereby, the third spring element **804**). The second electrically conductive path may be insulated from the first electrically conductive path when the third spring element **804** is not in contact with the member **806**. Accordingly, the multi-stage springs $\mathbf{802}_{A-B}$ may be utilized as a switch for selectively making electrical contacts (e.g., between the third spring element **804** and the member **806**).

In some embodiments, as shown in FIG. **8**C, a multi-stage spring $\mathbf{802}_C$ may be provided for making selective contact between a contact surface of a first member $\mathbf{806}_A$ and a contact surface of a second member $\mathbf{806}_B$. In some embodiments, such contact may be utilized to provide an electrical switch. For example, the first member $\mathbf{806}_A$ and the second member $\mathbf{806}_B$ may be at least partially fabricated from one or more electrically conductive materials to provide an electrical pathway that is open when the switch is open (e.g., when the multi-stage spring is relaxed.) The multi-stage spring $\mathbf{802}_C$ may be similar to the multi-stage springs $\mathbf{802}_A$, $\mathbf{802}_B$ described in FIGS. **8**A-B with the addition of a tip **805** disposed on the third spring element **804** (or whichever ultimate spring element is desired to make contact with the members $\mathbf{806}_A$, $\mathbf{806}_B$.). The tip **805** may be configured to contact both members $\mathbf{806}_A$, $\mathbf{806}_B$ upon sufficient deflection of the multi-stage spring $\mathbf{802}_C$. In some embodiments, the tip **805** may also be configured to wipe both members $\mathbf{806}_A$, $\mathbf{806}_B$ upon deflection of the multi-stage spring $\mathbf{802}_C$ beyond initial contact with the members $\mathbf{806}_A$, $\mathbf{806}_B$.

In embodiments where electrical contact is desired, the tip **805** may be fabricated from one or more conductive materials, may be coated with one or more conductive materials, or may have an electrically conductive portion coupled to the tip **805**. For example, FIG. **9**A depicts an illustrative schematic side view of a tip **805** in accordance with some embodiments of the invention. In the embodiment shown in FIG. **9**A, the tip **805** includes a base **902** disposed at an end of the third spring element **804**. The tip **805** further includes a conductive portion **904** configured to contact both members $\mathbf{806}_A$, $\mathbf{806}_B$ (as shown in FIG. **8**C). The conductive portion **904** may be a conductive coating (such as a deposited or plated coating), a thin sheet or foil that may be coupled to the base **902**, a thin conductive plate that is machined or bent to correspond to the geometry of the base **902**, or like material and configuration suitable for conducting electrical current in a desired application. In some embodiments, as shown in FIG. **9**B, a conductive portion **906** configured to contact both members $\mathbf{806}_{A-B}$ may be disposed in a corresponding recess in the base **902**. The conductive portion **906** may comprise one or more pieces of conductive material that is machined or otherwise formed into a desired shape suitable for contacting members $\mathbf{806}_{A-B}$. The geometry of the tip **805** (including the base **902**, the conductive portion **904**, and/or the conductive portion **906**) shown herein is illustrative only and other geometries are contemplated for either or both of the contact and non-contact portions of the tip **805**, such as curves, chevrons (vees), or the like.

In some embodiments, the wipe of the members by the multi-stage spring may be provided by elements other than the final spring element of the multi-stage spring. For example, in some embodiments, the tip **805** may be disposed at an end of a spring element (such as the third spring element **804**) that is not configured to wipe the members $\mathbf{806}_A$, $\mathbf{806}_B$ (shown in FIG. **8**C) upon continued deflection past initial contact therewith. In some embodiments, the tip **805** itself may be configured to provide the desired wipe motion. For example, FIGS. **10**A-C depict non-limiting examples of tips **805** suitable for use with multi-stage springs in accordance with some embodiments of the invention. In embodiments represented by FIG. **10**A, the tip **805** may include a base **1002** having two contacts $\mathbf{1004}_A$ that are each angled with respect to the respective member **806**A, **806**B with which the contact $\mathbf{1004}_A$ will engage. Similarly, as shown in FIG. **10**B, the base **1002** may include two contacts $\mathbf{1004}_B$ that are angled in outwardly opposing directions. In some embodiments, as shown in FIG. **10**C, the base **1002** may include two contacts $\mathbf{1004}_C$ that are angled in inwardly opposing directions. In some embodiments, the non-limiting examples of tip configurations shown in FIGS. **10**A-C may be combined with the non-limiting examples of the contacts depicted in FIGS. **9**A-B. It is contemplated that still other combinations of tip configurations, contacts, and spring configurations may also be utilized to provide a multi-stage spring in accordance with the teachings of the present invention.

In some embodiments, the multi-stage spring may have a tip configuration that may provide more even contact between multiple contact points (such as between a tip similar to the tip **805** and members $\mathbf{806}_{A-B}$). For example, in some embodiments, and as depicted in FIG. **11**A, the tip **804** of the multi-stage spring (such as in embodiments similar to FIG. **8**C) may initially come into contact with the members $\mathbf{806}_{A-B}$ substantially concurrently, or the tip **805** may provide substantially equal pressure against both members when a force, F, is applied to the multi-stage spring to cause it to come into contact with the members $\mathbf{806}_{A-B}$. As the force is increased, or as the wiping movement begins, increasingly higher contact force will be applied on member $\mathbf{806}_B$, and less on member $\mathbf{806}_A$ as the entire tip **805** wipes and rotates (as shown by arrows **1150**), thereby causing contact resistance variation between the members $\mathbf{806}_{A-B}$. In some embodiments, and as depicted in FIG. **11**B, the tip **805** may rotate sufficiently to disengage, or lose contact with, member $\mathbf{806}_A$.

In some embodiments, one or more of the tip **805**, the member $\mathbf{806}_A$, and/or the member $\mathbf{806}_B$ may be configured to compensate for the wipe and/or rotation of the tip **805** (as shown by arrows **1250**). For example, in some embodiments, and as shown in FIG. **12**A, the member $\mathbf{806}_A$ may be provided at an angle configured to account for the rotation of the tip **805**, which may facilitate making the resultant contact forces more even between the two members $\mathbf{806}_{A-B}$. Providing the member $\mathbf{806}_A$ at an angle may also advantageously facilitate keeping even contact along the surface of the members $\mathbf{806}_{A-B}$ as the tip **805** provides wipe of the respective surfaces of the members $\mathbf{806}_{A-B}$.

In some embodiments, a mechanism may be provided to facilitate rotation, or pivoting, of the tip **805** (and/or one or more of the members $\mathbf{806}_{A-B}$) while maintaining relatively even contact pressure between the tip **805** and the members $\mathbf{806}_{A-B}$ as the tip **805** wipes the members $\mathbf{806}_{A-B}$ (as shown by arrow **1252**). Examples of suitable mechanisms include hinges, flexures, springs, or the like. In some embodiments, the k value, if any, of the mechanism may provide an additional stage in the range of movement of the multi-stage spring (e.g., the multi-stage spring while have a certain cumulative k value before and after engagement of the mechanism). The mechanism may be provided at any suitable location in the multi-stage spring or in the members. For example, in some embodiments, and as depicted in FIG. **12**B, a spring **1200** may be provided to facilitate rotation of the tip **805** and maintain more even contact pressure between the tip **805** and the members $\mathbf{806}_{A\text{-}B}$. Although shown disposed in the third spring element **104**, the spring **1200** (or other mechanism) may be disposed in other locations as well, such as in the tip **805**, in one or more of the members $\mathbf{806}_{A\text{-}B}$, or the like.

The components, or elements, of the multi-stage spring assemblies disclosed herein may be fabricated from any suitable materials that may provide the desired characteristics for which the various assembly components provide. For example, the spring elements may be fabricated from materials providing the desired k values and range of motion of the individual spring elements without damaging the assembly. In addition, where the multi-stage spring assemblies are used to make electrical contacts, such as in switching applications, the multi-stage spring assembly may be at least partially fabricated from (including coated with) suitable conductive materials, such as metals, noble metals, or semi-noble metals (e.g., copper, aluminum, gold, rhodium, palladium, alloys thereof, or the like). For example, in some embodiments, the multi-stage spring assembly may be at least partially fabricated from silicon, or in some embodiments, single crystal silicon. In some embodiments, the multi-stage spring assembly may be lithographically fabricated from silicon. In some embodiments, the multi-stage spring assembly may be partially lithographically fabricated from silicon and the tip (e.g., **804**, **805**) may be formed from a metal by a suitable process, such as plating, or the like.

As described above with respect to FIGS. **8**A-C, multi-stage springs in accordance with embodiments of the invention may provide stages of increasing k values over a desired range of deflections of the multi-stage spring. Such incremental increases in k values at desired stages of deflection of the spring may advantageously be utilized to store increased quantities of mechanical energy in the multi-stage spring assembly when the force applied to actuate the multi-stage spring is increases exponentially. Such exponentially increasing forces may be obtained when using, in a non-limiting example, a gap closing electrostatic actuator to apply the force to drive the spring. Of course, any of the multi-stage springs **8**A-C can be used with any actuator and any tip (described herein). Moreover, FIGS. **8**A-C illustrate only exemplary multi-stage springs, and other configurations are possible that fall within the scope of the described invention.

For example, FIG. **13** depicts a graph showing the force in millinewtons (axis **1304**) versus the distance traveled, y, in micrometers (axis **1302**) for an electrostatic actuator having a variety of voltages applied (a first voltage shown by **1306**, a second voltage shown by **1308**, and a third voltage shown by **1310**) and an exemplary multi-stage spring assembly (**1312**). As shown by lines **1306**, **1308**, and **1310** the electrostatic force generated by a gap-closing actuator increases exponentially as the gap closes (e.g., as the actuator moves a longer distance as the electrodes approach a closed position).

As shown illustratively with respect to line **1310**, the mechanical force generated, or stored as potential energy within the multi-stage spring, may be advantageously made to more closely follow the curve of the electrostatic force generated by the actuator (e.g., line **1310** in this illustration). For example, a portion $\mathbf{1312}_A$ corresponds to the deflection of a first stage or spring element, portion $\mathbf{1312}_B$ corresponds to the engagement of a second stage or spring element, and portion $\mathbf{1312}_C$ corresponds to the engagement of a third stage or spring element. As can be readily seen from extension of the portion $\mathbf{1312}_A$, a spring or spring assembly having a linear k value over the desired range of travel would generate and store much less energy within the spring.

The line **1312** shown in FIG. **13** is illustrative of some embodiments of a multi-stage spring. Greater numbers of stages or spring elements may be implemented in a multi-stage spring in order to more closely follow the curve of the actuator force applied over the same range of travel (e.g., to more closely trace the force applied by the actuator). Thus, the multi-stage spring may provide a significant advantage as compared to single-stage linear springs conventionally used with electrostatic gap-closing actuators—embodiments of multi-stage springs as disclosed herein may advantageously store a greater magnitude of restoring force to facilitate overcoming contact stiction between contacts, for example, when used in switching applications.

As discussed above, the multi-stage spring assemblies in accordance with some embodiments of the invention may be utilized with an actuator to control the operation thereof (e.g., to control the deflection of the multi-stage spring). Examples of suitable actuators may be electrically, mechanically, or electromechanically driven and may vary in size to suit the application. In some embodiments, the actuator may be a micro-electromechanical system (MEMS) device, such as an electrostatic gap closing actuator, a comb drive, combinations thereof, or the like. Non-limiting examples of suitable MEMS actuators, such as electrostatic gap closing actuators, comb drives, angled gap closing actuators, partitioned MEMS actuators, or multi-stage MEMS actuators, are described in more detail below.

Actuator Examples

As discussed above, MEMS switches in accordance with embodiments of the present invention may be utilized with various actuating mechanisms to control the operation of the switch (e.g., any actuator provided herein may be used with any of the springs, contact elements, switches, or the like, in accordance with the teachings disclosed herein). Such actuators may be conventional, such as certain MEMS comb-drive or gap closing electrostatic actuators, or the like. In addition, in some embodiments, inventive MEMS comb-drive or gap closing electrostatic actuators may be provided, alone or in combination, with the embodiments of springs and contact arrangements as discussed above.

For example, conventional MEMS electrostatic actuator designs typically use one of either parallel-plate or comb actuating mechanisms. MEMS parallel-plate mechanisms provide a force characteristic that is inversely proportional to the square of a remaining gap distance between two parallel plate electrodes. This arrangement provides an electrostatic force that is very strong only when the gap between the plates is small. In contrast, MEMS comb actuators typically provide a larger travel distance with a force characteristic that is constant to the first order with respect to the travel distance of the actuator. However, the force provided by a comb actuator is smaller in comparison to the parallel-plate force when the gap is small. Consequently, such actuators provide either high-force and low travel distance (in the parallel-plate case), or low-force and larger travel distance (in the comb case).

FIG. **14** depicts a partitioned electrostatic actuator **1404** that may include at least two actuating mechanisms according to some embodiments of the invention. The at least two actuating mechanisms may be the same or different and may be configured to operate together to provide an increased actuation force for a given range of travel of the actuator. In some embodiments, both comb and parallel-plate MEMS electrostatic actuating mechanisms may be provided in a single actuator, such that the comb actuator portion provides a large travel distance that moves the parallel-plate actuator portion to a small gap distance, at which point the parallel-plate actuator becomes dominant in producing a high level of electrostatic force.

For example, in some embodiments, the partitioned electrostatic actuator **1404** may include a comb drive electrostatic actuator **1460** and a parallel plate, or gap-closing, electrostatic actuator **1470**. The combination of the comb drive and gap-closing actuators may facilitate providing a larger range of motion characteristic of the comb drive actuator along with a greater actuation force characteristic of the gap-closing actuator.

In some embodiments, a movable frame **1420** may be provided having a plurality of movable electrodes **1422** extending therefrom in a region corresponding to the comb drive electrostatic actuator **1460** and a movable parallel plate electrode **1427** extending therefrom in a region corresponding to the gap closing electrostatic actuator **1470**. The movable frame **1420** may be movable in a direction as shown by arrows **1450**. A fixed frame **1425** may be provided having a plurality of fixed electrodes **1424** extending therefrom in an opposing, interleaved configuration with the plurality of movable electrodes **1422** within the region corresponding to the comb drive electrostatic actuator **1460** and a flat region **1428** generally opposed with the parallel plate **1427** in the region corresponding to the gap-closing electrostatic actuator **1470**. A spring **1426** may be provided (for example, coupled to the movable frame **1420**) to store a restoring force that may facilitate returning the actuator **1404** to an open position. The spring **1426** is simply representative of various spring shapes and/or configurations which are contemplated.

In operation, a voltage potential may be applied to the actuator **1404**. Initially, the gap between the gap-closing electrostatic actuator portion **1470** is large and, therefore, the attractive force is small. However, the comb drive portion **1460** of the actuator **1404** operates to bring the movable electrode **1427** of the gap-closing electrostatic actuator **1470** closer to the opposing fixed electrode **1428**, at which point the increased force of attraction between the electrodes **1427** and the fixed portion **1425** provides a high force of attraction. Thus, the actuator **1404** may advantageously provide a large travel distance as well as a high force at the end of the displacement range.

The force-displacement characteristic of a normal parallel plate, or gap-closing electrostatic actuator is flat in the initial displacement regime and steep in the final displacement regime (e.g., the change in the attractive force is small initially when the gap between opposing electrodes is larger, but rapidly increases as the gap between the opposing electrodes nears the minimum; see, for example, FIG. **13**). This characteristic limits the potential wiping motion applied by a switch due to the large attractive force being generated mainly over a small range of motion. This constraint may be ameliorated by, for example, higher voltages, larger actuator areas, and/or using higher energy actuators, but these solutions are limited by product requirements. Ultimately, control of the gap distance is a powerful parameter to attain a high force, but it limits the application of a wipe motion by a contact element coupled to the actuator.

To overcome this deficiency, and to attain both high force and large displacement, a parallel plate gap-closing actuator may be provided having the opposing electrodes rotated at an angle with respect to the direction of movement. Rotating the electrodes relative to the direction of movement allows a narrower gap to be provided between adjacent electrodes. The narrower gap allows for higher energy actuator, which in turn outputs a higher force. The factor of improvement is approximately $1/\cos\theta$ relative to normal parallel plate actuator.

For example, FIG. **15** depicts an angled parallel plate actuator **1504** similar to the gap closing actuator discussed above with respect to FIG. **2**, however, having angled electrodes that may provide a larger range of motion of the actuator **1504** and/or that may provide a higher attractive force. In some embodiments, a movable frame **1520** may be provided having a plurality of movable electrodes **1522** extending therefrom at a non-perpendicular angle with respect to the direction of movement of the actuator **1504** (indicated by arrows **1550**). A fixed structure **1525** may be provided to support a plurality of fixed electrodes **1524** in an orientation that is generally parallel with the plurality of fixed movable electrodes **1522** and interleaved therewith such that by providing a voltage differential to the fixed and movable electrodes **1524**, **1522**, motion of the actuator **1504** may be controlled.

As shown in more detail in FIG. **15**A, a distance y in the direction of movement is greater than the normal distance, or gap g, between the respective pairs of electrodes **1522**, **1524** due to the non-perpendicular angle of the electrodes with respect to the direction of movement. Specifically, the y-motion traveled upon closing the actuator **1504** (e.g., due to the closing of the gap between the electrodes **1522**, **1524**) will be equivalent to the gap g divided by the cosine of the angle θ (defined between the direction of travel, y, and the perpendicular extending between the respective electrodes). As such, for a given voltage potential applied, the actuator **1504** provides the benefit of an actuator having a smaller gap (generating higher electrostatic attractive forces) in combination with a longer range of motion (as compared to conventional actuators providing similar attractive forces at similar voltages). The angle of the electrodes may be adjusted to provide a balance between the range of motion and the force generated. For example, a lesser angle (e.g., a smaller θ, as shown in FIG. **15**A) will provide a lesser range of motion, y, while a greater angle (e.g., a larger θ, as shown in FIG. **15**A) will provide a greater range of motion, y.

The symmetric configuration of the opposing electrodes (e.g., fixed electrodes **1524** and movable electrodes **1522**) on either side of the fixed structure **1525** can provide stability of the actuator **1504** by balancing the forces generated non-parallel to the direction of movement. In addition, the utilization of restoring springs **1526** may further provide stability of the actuator **1504** while further facilitating returning the actuator **1504** to an open position when the voltage potential for actuation is removed.

The length of the movable frame **1520** and fixed structure **1525**, and the number of opposing electrodes extending therefrom, may be controlled to generate a desired force for a given actuation voltage. In some embodiments, the movable frame **1520** may be configured to interface with a plurality of fixed structures **1525** (for example, four fixed structures **1525** are illustratively depicted in FIG. **15**, although greater or fewer are contemplated) to further control the desired attractive force generated by the actuator **1504** at a given applied voltage potential.

As such, an electrostatic gap-closing actuator has been provided that may provide both a larger range of motion and a larger force generated for a given voltage applied to the actuator. Such an actuator may also advantageously facilitate the generation or application of longer wipe lengths in contact elements controlled by the actuator.

As discussed above, conventional gap-closing parallel plate actuators generate large forces, but with small displacement. However, for some applications, such as for providing wipe in a switch as described herein, both large force and large displacement is desired for wiping on a contact material of the switch. To overcome this deficiency, a multi-step gap-closing actuator may be provided that steps through a total range of motion with multiple gap-closing actuators linked in series. Using such an actuator, the force-displacement curve of the actuator may be raised in the earlier portion of the gap closing distance in exchange for a smaller final resultant force at the final gap closing distance.

For example, FIG. **16** depicts a multi-stage gap closing actuator **1604** comprising a plurality of actuating stages **1605**$_1$ to **1605**$_n$ (illustratively movable as shown by arrows **1650**). In the embodiment depicted in FIG. **16**, four stages **1605** are shown, although greater or fewer stages may be utilized. The multi-stage gap closing actuator **1604** may include a movable frame **1620** having a plurality of openings corresponding to each stage **1605**. The movable frame **1620** generally supports a plurality of movable electrodes **1622** in each stage **1605**$_{1-n}$. A fixed structure **1625** may be provided within each stage **1605**$_{1-n}$ for supporting a corresponding plurality of fixed electrodes **1624** in an opposing and interleaved configuration with the plurality of movable electrodes **1622**.

The first stage **1605**$_1$ may be provided with a first gap **1640**$_1$ between the respective fixed and movable electrodes **1624**, **1622** contained within the first stage **1605**$_1$. The successive gaps between electrodes in each adjacent stage is increasingly larger as shown by gaps **1640**$_2$, **1640**$_3$, and **1640**$_n$. As such, when the gap **1640**$_1$ is closed in the first stage **1605**$_1$, the gaps **1640**$_2$, **1640**$_3$, and **1640**$_n$ are concomitantly reduced by the same amount, thereby bringing the electrodes in stage **1605**$_2$ close enough to provide a sufficiently high attractive force therebetween to further continue closing the gap **1640**$_2$, which further brings the gaps **1640**$_3$ and **1640**$_n$ closer together and so on until the final gap **1640**$_n$ is closed.

The fixed structure **1625** in each of the first and in any intervening stages, for example, as shown in FIG. **16**, the first stage **1605**$_1$, the second stage **1605**$_2$, and the third stage **1605**$_3$, each contain one or more springs **1636** to facilitate allowing the fixed electrodes **1624** respectively coupled to the fixed structure **1625** to move as necessary to allow each subsequent stage to close.

Thus, the multi-stage gap-closing actuator **1604** advantageously may facilitate increasing the range of movement of the actuator without utilizing higher voltage or a larger die areas, thereby making such an actuator suitable for low voltage requirements (e.g., a less than 3 volt requirement, as used, for example, in cell phone applications) and thereby providing a lower cost per die for fabrication of the actuator.

Illustrative Embodiment

As discussed above, the RF switch of the present invention may have various contact configurations and/or actuator configurations. As an illustrative example of one such configuration, FIG. **17** depicts a schematic top view of a MEMS switch **1750**. The MEMS switch **1750** includes a multi-stage spring **1702** in accordance with some embodiments of the present invention coupled to an actuator **1710** for controlling the deflection of the multi-stage spring **1702** to selectively make contact with members **1706**$_A$ and **1706**$_B$. Control of the actuator **1710** thereby controls operation of the MEMS switch **1750** (e.g., the opening and/or closing of the MEMS switch **1750**).

In the embodiment shown in FIG. **17**, the actuator **1710** may illustratively be an electrostatic gap-closing actuator having a movable frame **1712** for supporting a plurality of movable electrodes **1714** coupled thereto. A fixed structure **1716** may be provided for supporting a plurality of fixed electrodes **1718** configured to interface with the movable electrodes **1714**. The fixed structure **1716** may be disposed within the movable frame **1712** or otherwise configured to support the fixed electrodes **1718** in a desired position with respect to the movable electrodes **1714**.

The fixed electrodes **1718** may be interleaved with and spaced apart from the movable electrodes **1714**. At rest, the fixed electrodes **1718** and the movable electrodes **1714** are disposed at a first distance from each other along their respective major axes, and at least slightly off-center with respect to the gap between any two adjacent pairs of fixed electrodes **1718** or movable electrodes **1714** (i.e., the gap between the long sides of the electrodes is at least slightly greater on one side of a respective electrode than the other to facilitate consistent directional movement of the movable electrodes **1714** towards the nearer respective fixed electrode **1718**, and thereby, consistent directional movement of the actuator **1710**). Application of a voltage potential between the fixed electrodes **1718** and the movable electrodes **1714** causes the movable frame **1712** and the movable electrodes **1714** to move towards the fixed electrodes **1718**. In the embodiment depicted in FIG. **17**, such motion is in an upwards direction. As the gap between the movable electrodes **1714** and the fixed electrodes **1718** decreases, the electrostatic attraction therebetween increases, thereby applying a greater force to the multi-stage spring **1750** (as described with respect to FIG. **11**, above).

A plurality of springs, for example at least partially provided by the multi-stage spring **1750**, may be utilized to store a mechanical restoring force that may facilitate overcoming any contact stiction that may exist between the movable and fixed electrodes **1714**, **1718**, and/or between the contacts being made with the switch (e.g., between the multi-stage spring **1702** and the members **1706**$_{A-B}$). Such restoring force facilitates returning the multi-stage spring **1702**, and the actuator **1710** to a resting position (e.g., in the embodiment depicted in FIGS. **17** and **18**, a position wherein the MEMS switch **1750** is open).

For example, FIG. **18** depicts a close-up view of the illustrative multi-stage spring **802** shown in FIG. **17** that details illustrative numbers and positions of springs that may be utilized to store mechanical energy during actuation of the switch, as described above. As shown in FIG. **18**, a first spring **1802** may be coupled between the movable frames **1712** of the actuator **1710** and a fixed element **1808** (although FIG. **18** depicts a symmetric arrangement of springs and fixed elements, the description is limited to one side of the figure for ease of understanding).

The first spring **1802** may be configured to interface with or engage with a second spring **1806** upon a desired quantity of deflection of the first spring **1802** (e.g., upon application of an actuation voltage to the actuator **1710** to cause the actuator **1710** to begin to move, the first spring **1802** immediately begins to deflect and store mechanical energy and will engage with the second spring **1806** after continuing to move for a certain distance). In some embodiments, a protrusion **1804** may be provided to facilitate engaging the second spring **1806**. The protrusion **1804** may be configured to define a desired gap between the protrusion **1804** and the second spring **1806** such that the second spring **1806** will be engaged upon a desired quantity of deflection of the first spring **1802**. In the embodiment shown in FIG. **18**, the second spring **1806** is shown as an extension from the fixed member **1808**. However, it is contemplated that the second spring **1806** may be coupled to a different fixed member or otherwise disposed in a desired location to provide the stages of operation as described herein.

Upon continued movement of the actuator **1710**, a third spring **1814** may be engaged when a contact **1816** disposed at a distal end thereof comes into contact with contacts $\mathbf{1706}_A$ and $\mathbf{1706}_B$ to close the switch. The third spring **1814** may be configured to provide a wiping action between the contact **1816** and the contacts $\mathbf{1706}_A$ and $\mathbf{1706}_B$ (e.g., a lateral movement therebetween) as the actuator **1710** continues to move towards a closed position. The wiping, and subsequent unwiping motion upon retraction of the actuator **1710** and thereby the multi-stage spring **1702**, may facilitate overcoming any contact stiction between the contact **1816** and the elements $\mathbf{1706}_A$ and $\mathbf{1706}_B$. The wiping motion may further facilitate breaking through any oxide layer or particles or other contaminants that may exist between the contact **1816** and the elements $\mathbf{1706}_A$ and $\mathbf{1706}_B$, which may improve the operation of the switch (e.g., signal quality, switch lifetime, or the like).

As the actuator **1710** closes, the first spring **1802** of the multi-stage spring **1702** provides a first spring constant (k value) as the spring assembly is deflected up to a first distance (e.g., until the engagement of the second spring **1806**). Once engaged, the second spring **1806** provides a greater, second spring constant (k value) when deflected beyond the first distance and up to a second distance (e.g., until the engagement of the third spring **1814**). Once the third spring **1814** is engaged, a greater, third spring constant (k value) is provided as the multi-stage spring **1702** is deflected beyond the second distance and up to a third distance.

The stored mechanical energy of the actuated multi-stage spring **1702** biases the spring assembly in a direction away from the contact surface, thereby facilitating return of the multi-stage spring **1702** to its resting position and helping to overcome any contact stiction that may exist between the contacts (e.g., between contact **1816** and contacts **1806***a* and **1806***b* and/or between electrodes of the actuator **1710**).

In some embodiments, the multi-stage spring assembly may be configured to have a limited range of motion (e.g., by providing a stop or other mechanism for preventing excessive travel of the multi-stage spring). In some embodiments, the limited range of motion may facilitate preventing the moving and fixed electrodes of an electrostatic, gap-closing actuator from coming into contact with each other, thereby preventing any contact stiction from developing between the electrodes and facilitating extending the lifetime of the actuator. For example, in the embodiment depicted in FIGS. **17-18** a protrusion **1812** may be provided to interface with a corresponding protrusion **1810** that limits the travel of the multi-stage spring **1702** towards the closed position. The location and geometry of the protrusions **1810**, **1812** are illustrative only and many other geometries and configurations may be utilized to limit the travel of the multi-stage spring **1702**.

Thus, embodiments of multi-stage spring assemblies that provide variable spring compliance that shapes the mechanical characteristics of the spring system have been described herein. In some embodiments, the mechanical characteristics of the spring system may be shaped to conform to forces applied by an actuating means coupled to the multi-stage spring system. The multi-stage spring system may offer different compliant levels at different deflection locations. In a non-limiting example, the multi-stage spring system may be utilized to provide a compact, high-density, low-voltage MEMS switch. For example, the multi-stage spring system can be used as part of, or in conjunction with, a MEMS parallel-plate actuator (e.g., an electrostatic gap-closing actuator) for various applications, including RF switches. The multi-stage spring system may advantageously provide higher contact-breaking forces in such a MEMS switching device.

In some embodiments, a MEMS switch in accordance with the teachings provided herein may be provided in an electronic device. For example, FIG. **19** depicts an electronic device **1900** having an input circuit **1902** for providing a signal and an output circuit **1906** for receiving the signal from the input circuit **1902**. A MEMS switch **1904** may be provided to selectively couple the input circuit **1902** to the output circuit **1906** as described in more detail above.

The electronic device may be any electronic device having an internal electronic switch that controls aspects of the operation thereof. Non-limiting examples of suitable electronic devices include portable and non-portable electronic devices (for example, portable phones (e.g., cell phones, smart phones, or the like), personal digital assistants, music players (e.g., radios, digital music players, or the like), digital cameras and/or video cameras, electronic games, navigational devices, computers and/or computing devices, televisions and/or video players, multimedia players, or the like), or the like. Such electronic devices may portable, non-portable, installed electronic devices (such as any of the preceding installed in a home, vehicle, or other location), or the like.

Thus, a MEMS switch and apparatus or devices incorporating the same have been provided herein. In some embodiments, the MEMS switch may advantageously wipe a contact surface of the switch, which may enhance switch performance and extend switch lifetime. In some embodiments, the switch may include a multi-stage spring system that advantageously stores a greater restoring force (as compared to conventional switches) that may facilitate returning the switch to an open position when the switch is turned off. In some embodiments, the switch may include one or more of various contact elements that may advantageously provide one or more of a wipe motion against a contact pad, an increased wipe for a given actuation distance, or the like. In some embodiments, the switch may include one or more of various electrostatic actuators that may advantageously provide one or more of a higher force generated for a given voltage potential, a greater range of motion of the actuator, or the like.

While the foregoing is directed to embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

The invention claimed is:

1. A MEMS switch, comprising:

a resilient contact element comprising a resilient beam and a tip configured to wipe a contact surface; and

a MEMS actuator comprising the contact surface and having an open position that maintains the tip and the contact surface in a spaced apart relation and a closed position that brings the tip into contact with the contact surface, wherein the resilient contact element and the MEMS actuator are disposed on a substrate and are movable in a plane substantially parallel to the substrate.

2. The switch of claim **1**, wherein the resilient contact element is coupled to the actuator.

3. The switch of claim **1**, wherein the MEMS actuator is at least one of a comb actuator, a gap closing actuator, an angled gap closing actuator, a partitioned MEMS actuator, or a multi-stage actuator.

4. The switch of claim **1**, wherein the actuator provides a contact force greater than or on the order of mN at an actuation voltage of less than or equal to about 3 Volts.

5. The switch of claim **1**, wherein at least one of the contact surface or the tip comprises rhodium.

6. The switch of claim **1**, wherein the actuator and the resilient contact element are lithographically formed on a common substrate.

7. The switch of claim **1**, wherein the resilient contact element is part of a spring assembly having a first spring constant when deflected up to a first distance, a greater, second spring constant when deflected beyond the first distance and up to a second distance, and a greater, third spring constant when deflected beyond the second distance and up to a third distance, and wherein the spring assembly stores mechanical energy when deflected towards a contact surface that biases the spring assembly away from the contact surface.

8. A MEMS switch, comprising:

a resilient contact element comprising a beam flexible about a pivot point and a having a tip disposed proximate an end of the beam and configured to engage a contact surface; and

a MEMS actuator coupled to the resilient contact element and having an open position that maintains the tip and the contact surface in a spaced apart relation and a closed position that brings the tip into contact with the contact surface, wherein the actuator is directly engaged with the beam at a point remote from the pivot point, and wherein the resilient contact element and the MEMS actuator are disposed on a substrate and movable in a plane substantially parallel to the substrate.

9. The switch of claim **8**, wherein operation of the actuator pulls the beam towards the actuator.

10. The switch of claim **8**, wherein the actuator is coupled to the beam on the same side of the pivot point as the tip.

11. The switch of claim **8**, wherein the actuator is coupled to the beam on a side of the pivot point opposite the tip.

12. The switch of claim **8**, further comprising:

a selectively engageable locking mechanism configured to bias the tip into contact with the contact surface and wherein operation of the actuator selectively opens the switch.

13. The switch of claim **8**, further comprising:

a second resilient contact element comprising a beam and a tip configured to wipe a contact surface, the resilient element and the second resilient element both coupled to the actuator.

14. The switch of claim **13**, wherein actuation causes the resilient element and the second resilient element to move in the same direction.

15. The switch of claim **13**, wherein actuation causes the resilient element and the second resilient element to move in opposite directions.

16. The switch of claim **8**, wherein the pivot point of the beam is closer to the actuator than to the tip.

17. The switch of claim **8**, wherein the pivot point of the beam is closer to the tip than to the actuator.

18. The switch of claim **1**, wherein:

the MEMS actuator comprises a movable portion that is movable between the open position and the closed position, and

the movable portion comprises the contact surface.

19. The switch of claim **18** further comprising mechanical energy storing means for storing mechanical energy as the movable portion moves from the open position to the closed position sufficient to move the movable portion from the closed position back to the open position.

20. The switch of claim **19**, wherein the mechanical energy storing means comprises mechanical springs coupled to the movable portion of the MEMS actuator.

21. The switch of claim **20** further comprising a fixed structure, wherein the mechanical springs are also coupled to fixed structure.

22. The switch of claim **1**, wherein the resilient beam is linear.

23. The switch of claim **1**, wherein the resilient beam is non-linear.

24. The switch of claim **1**, wherein the resilient beam comprises a reinforcement member.

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